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SOME PHASE RELATIONS IN THE HYDROTHERMALLY ALTERED ROCKS OF PORPHYRY COPPER DEPOSITS[1]

S. C. CREASEY

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ABSTRACT

The application of ACF and AKF diagrams to the hydrothermal alteration in porphyry copper deposits aids in the recognition of the critical components, and the characteristic mineral phases permit the distinction of one alteration facies from another.

The somewhat meager chemical and mineralogical data suggest three principal alteration facies, herein called the propylitic, argillic, and potassium silicate facies. The ACF diagram applies to the propylitic alteration. The critical components are Al_2O_3, CaO, and (FeO + MgO +

[1] Publication authorized by the Director, U. S. Geological Survey.

MnO), and the characteristic minerals are muscovite (sericite), epidote, chlorite, and a member of the carbonate group. The AKF diagram applies to the argillic and potassium silicate facies. The critical components are Al_2O_3, K_2O, and (FeO + MgO + MnO). The characteristic minerals for the argillic facies are kaolinite (or other member of the group) and muscovite (sericite); and for the potassium silicate facies, muscovite (sericite), biotite, and K-feldspar.

For the propylitic facies, insufficient chemical analyses are available to show the chemical changes between the fresh and altered rock. For the argillic and potassium silicate facies, chemical analyses indicate a loss in aluminum, iron, magnesium, calcium, and sodium; and a gain in potassium, hydroxyl ion (water), and sulfur. The gain in potassium is about 60 percent greater for the potassium silicate facies than for the argillic.

INTRODUCTION

STUDIES of the alteration products in porphyry copper deposits have increased at a rapid rate since Lovering (11) pointed out the clay and sericitic alteration adjacent to the tungsten veins in Boulder County, Colorado. Among the studies pertinent to porphyry copper deposits are those of Schwartz (18) on the San Manuel deposit, Arizona; Anderson (1) on the Bagdad deposit, Arizona; Gilluly (4) on the Ajo deposit, Arizona; Peterson, Gilbert, and Quick (14) on the Castle Dome deposit, Arizona; Kerr and others (7) and Leroy (8) on the Santa Rita deposit, New Mexico; Kerr (6) on the Silver Bell deposit, Arizona; Stringham (20) on the Bingham deposit, Utah; and Sales and Meyer (15, 16) on the Butte deposit, Montana. Because of the usefulness of their studies, Lovering and others (12) must be included in this list, although they did not work on a porphyry copper deposit. Each of the workers thoroughly described the alteration in a particular deposit or district, and most supported their observations by chemical analyses of fresh and altered rocks within and adjacent to the ore deposit.

Anderson (1, p. 622–623) compared the principal chemical constituents, expressed in milligrams per cubic centimeter of altered and unaltered rocks, for the deposits at Bagdad, Ajo, Castle Dome, and Ely. He summarizes as follows: "If any general statements can be made about the porphyry copper deposits for which there are chemical data, it would be that lime is more readily leached than soda during alteration; potash is usually added; magnesia may be added or slightly leached in some facies, but it is definitely leached in other facies. The iron content does not increase, except locally, and in general, iron is leached even in sulfide ore. Silica and alumina are not appreciably changed during alteration. Perhaps the increased quartz content in the altered rocks is due to release of silica from other minerals during alteration."

Schwartz (17), after personally visiting many of the porphyry copper deposits for direct comparison, and after laboratory studies of the altered and fresh rocks from these deposits, generalized the alteration of the porphyry copper deposits into four types:

Sericitic and argillic alteration, quartz subordinate	Quartz-orthoclase alteration	Quartz-sericite-pyrite alteration	Biotitic alteration
1. Morenci, Arizona 2. Santa Rita (Chino), N. M. 3. Castle Dome, Arizona (in part) 4. San Manuel, Arizona	1. Bagdad, Arizona 2. Ajo, Arizona 3. Ely, Nevada 4. Bingham, Utah (in part)	1. Inspiration—Miami, Arizona 2. Ray, Arizona 3. Sacramento Hill, Arizona 4. Bingham, Utah (in part) 5. Castle Dome, Arizona (in part)	1. Bingham, Utah 2. Ely, Nevada 3. Bagdad, Arizona (in part) 4. San Manuel, Arizona (in part)

Other workers have pointed out individual similarities, but have not attempted to generalize for all porphyry copper deposits.

This article is a by-product of the comparison of the hydrothermal alteration at San Manuel with that in eight other porphyry copper deposits (Bagdad, Ajo, Ely, Chuquicamata, Bingham, Castle Dome, Santa Rita, and Morenci). Early geological work on the San Manuel deposit by Schwartz (18) was done during exploration before the deposit was opened for direct observation underground. Schwartz therefore was obliged to depend largely on surface exposures, logs, assays, and churn drill cuttings for his data. In 1954, I was assigned to continue the U. S. Geological Survey's investigation of the San Manuel deposit. By this time subsequent development had opened the deposit, and additional information on the type and extent of the mineralization was available to me. From the underground exposures, two distinct types of altered and mineralized rock were apparent: one formed the ore zone and the other the hanging wall. The footwall was not exposed, but from Schwartz's (18) descriptions, the alteration in the footwall is similar to that in the hanging wall.

The first part of the article comprises a brief description of the alteration in the nine deposits for the benefit of those not familiar with them. Following this I have used ACF and AKF diagrams commonly applied in the study of other types of metamorphism to aid in the recognition of the critical mineral phases in the hydrothermally altered rocks. In summary, the diagrams suggest that the hydrothermal alteration of the porphyry copper deposits results in three alteration facies: (1) a propylitic alteration, whose characteristic minerals are muscovite (sericite), epidote, chlorite, and a member of the carbonate group, (2) a potassium silicate alteration whose characteristic minerals are muscovite, biotite, and K-feldspar, and (3) an argillic alteration whose characteristic minerals are kaolinite [2] and muscovite (generally the fine-grained type commonly called sericite). Lastly I have given the chemical changes between the fresh and altered rocks, and so far as I am able, related them to the three alteration facies recognized here.

Investigators of different porphyry copper deposits describe considerable

[2] Kaolinite or any member of the kaolinite group. Henceforth kaolinite will be used in this sense to avoid the awkward phrase, "member of the kaolinite group."

variation within these three facies, but commonly they are based on the variation of the amount, or even the presence, of a mineral phase. Emphasis on the abundance can tend to obscure the fundamental similarities, even though the abundant mineral phase is a proper basis for further refinement.

I am indebted to D. E. White, E. W. Tooker, and H. T. Morris, all of the U. S. Geological Survey, for their constructive reviews of the manuscript and constructive discussions on the problems of hydrothermal alterations.

HYDROTHERMAL ALTERATION IN NINE PORPHYRY COPPER DEPOSITS

As part of the description of the individual deposits, I have related the alteration to one or more of the three alteration facies: propylitic, argillic, or potassium silicate. The use of these alteration facies is justified later in that part of the paper on phase relations.

San Manuel, Arizona.—All the quartz monzonite porphyry within a radius of three miles from the San Manuel deposit is altered. Away from the deposit, the alteration is propylitic; in the deposit, both argillic and potassium silicate alterations occur. They are, however, separate; the argillic alteration is in the footwall and hanging wall, whereas the potassium silicate alteration is in the ore zone.

The propylitic alteration is similar to that near the Castle Dome deposit described by Peterson, Gilbert, and Quick (14). The biotite is progressively altered to hydrobiotite(?) and then to chlorite with subordinate amounts of calcite, granular rutile, leucoxene, sericite, and iron oxide. The plagioclase phenocrysts become progressively more albitic, and the albitization is accompanied by the crystallization of calcite, epidote, and sericite. Quartz and K-feldspar are unchanged.

The mineral phases found in the potassium silicate alteration are albitic plagioclase, K-feldspar, quartz, biotite, sericite, kaolinite, chlorite, calcite, rutile, leucoxene, apatite, zircon, magnetite, pyrite, and chalcopyrite. Of these, chlorite, calcite, kaolinite, and perhaps leucoxene are believed to be unstable relicts from the propylitic alteration. Apatite and zircon are residual from the original rock, although apatite has recrystallized. New minerals believed to be stable phases are albitic plagioclase (may be metastable), biotite, K-feldspar, sericite, granular rutile, pyrite, and chalcopyrite. The place of kaolinite in the facies is uncertain. It occurred in about half of the examined specimens as an alteration of plagioclase, both alone, with calcite, and with sericite. In most specimens it does not appear to be altering to any other mineral, but in a few, it was altered to K-feldspar. On the basis of its microscopic appearance therefore it is metastable over most of the area affected by the potassium silicate alteration.

The potassium silicate facies does not completely destroy the original appearance of the porphyry. The plagioclase phenocrysts, which are the most conspicuous minerals in the fresh rock, maintain their approximate outline despite general intense alteration. Enough book biotites occur to give the same general effect as in the unaltered porphyry. The general appearance of this biotite does not reveal that it is regenerated from chlorite, which was a

propylitic alteration of the original biotite. The groundmass recrystallized, but to the unaided eye it is aphanitic, similar to that in the unaltered rock. The casual observer therefore might fail to recognize that the porphyry had been profoundly altered and recrystallized. Anderson and others (2) pointed out this aspect for the biotite-albite-orthoclase phase of altered quartz monzonite in the Bagdad porphyry copper deposit.

For the argillic facies, the major mineral phases listed in order of abundance are quartz, sericite, pyrite, and kaolinite. In addition, there are minor amounts of granular rutile, leucoxene, apatite, and zircon; both the rutile and apatite have recrystallized. Biotite alters principally to sericite, and to a minor extent to kaolinite, pyrite, and leucoxene. Plagioclase alters chiefly to a mat of fine-grained sericite, and to a lesser extent, to kaolinite.

Bagdad, Arizona.—Anderson (1) described a potassium silicate alteration of the quartz monzonite stock at Bagdad, Arizona. The texture of the unaltered rock ranges from porphyritic to seriate, and the rock consists chiefly of plagioclase (calcic oligoclase to andesine), orthoclase, quartz, book biotite, and hornblende.

Two alteration assemblages were recognized: biotite-albite-quartz-orthoclase, and quartz-orthoclase-sericite. The texture of the biotite-albite-quartz-orthoclase rock is granular. Quartz and orthoclase have increased; biotite has increased and recrystallized to a leafy habit. The secondary biotite is lower in iron and higher in magnesium. Plagioclase has decreased significantly—about equivalent to the anorthite content of the primary mineral. Sericite is a minor constituent.

The quartz-orthoclase-sericite rock locally shows a complete loss of the original texture, but elsewhere it contains relict plagioclase phenocrysts, now albitized. This rock differs from the biotite-albite-quartz-orthoclase assemblage in containing more orthoclase and sericite, and less albite and practically no biotite. Anderson (1, p. 615) believes the quartz-orthoclase-sericite assemblage represents a more advanced stage of alteration.

The Bagdad deposit is an excellent example of the potassium silicate alteration facies. The separation of two assemblages, which can be recognized individually in the outcrop, points out that subdivision of the facies is practical.

Ajo, Arizona.—The first phase of the alteration at Ajo resulted in replacement of the country rock (New Cornelia quartz monzonite) by pegmatite, which consists of K-feldspar (microcline and orthoclase), quartz, leafy biotite, and much leafy chlorite. In areas adjacent to the pegmatized zones, the groundmass of the New Cornelia quartz monzonite was replaced by K-feldspar, and the rock was silicified.

Sericite occurs nearly everywhere in the altered area and the plagioclase in the ore body is almost completely altered to albite. Because of much more K-feldspar than plagioclase in the pegmatized zones, sericitization and albitization of the plagioclase is less abundant than in the surrounding areas, and especially toward the east where pyrite is more abundant. Gilluly believes (4, p. 76) that the albitization and sericitization are a lower temperature alteration, and probably involved less transfer of material.

Gilluly recognized three types of chlorite. He believes that chlorite associated with quartz and microline probably was introduced as biotite and subsequently altered. In addition, the mafic minerals near the New Cornelia ore body were altered to pseudomorphous chlorite, and a third variety occurs as vein fillings and fine-grained replacement aggregates. The exact place of chlorite in the alteration process is thus most difficult to assess.

Magnetite, deposited in veins, closely followed the pegmatization, and following the magnetite, the sulfides were deposited.

Hydrothermal clay minerals do not occur at Ajo, and therefore there is no argillic alteration. Whether some of the chlorite indicates an early, or late, period of propylitic alteration is not clear, but the possibilities exist. Little doubt exists, however, that the great bulk of the alteration was of the potassium silicate type.

Ely, Nevada.—The weakest alteration at Ely, according to Spencer (19), involved the sericitization of the plagioclase and the incipient alteration of the hornblende to epidote, chlorite, and calcite. This is a propylitic alteration.

The alteration most closely associated with the copper ore resulted (1) in the destruction of the plagioclase, hornblende, and magnetite, (2) in the deposition of muscovite, brown biotite, pyrite, chalcopyrite, and calcite, and (3) in the reconstitution of the groundmass quartz and orthoclase. The groundmass of the thoroughly altered porphyry has a granulated appearance quite distinct from the unaltered rock. Phenocrystic orthoclase is either not attacked or is reconstituted in smaller grains. Quartz-orthoclase-biotite-sulfide veinlets seam the rock. Spencer (19, p. 55) thought that the rock was altered prior to the deposition of the veinlets, and that the veinlets were followed by the deposition of pyrite films in joint fractures.

The above description certainly places the alteration related to ore in the potassium silicate facies. The extent of the mild propylitic alteration is not given by Spencer, but presumably it was marginal or at least away from the deposit per se. Spencer mentions an intense alteration to sericite and quartz. This assemblage, however, contains nothing diagnostic for either the potassium silicate or the argillic facies. One might presume the former because of the lack of any other argillic alteration product.

Chuquicamata, Chile.—Lopez (10) has the most adequate description of the altered porphyry in the Chuquicamata deposit, although even his descriptions are rather short. He also gives analyses of the altered rocks and approximate mineral compositions for each type of alteration. Unfortunately some of the mineral compositions are not too compatible with the corresponding analysis, which makes the data difficult to interpret. Nevertheless considerable data are available.

Propylitic alteration marks the "transition rock" along the eastern margin of the deposit. Its most obvious manifestation is the chloritization of the ferromagnesian minerals. In addition, the list of minerals shows a marked increase in albite and a corresponding decrease in anorthite content of the plagioclase in the propylitic rock as compared to the unaltered porphyry. Propylitic alteration therefore seems well established.

Toward the deposit, the propylitic alteration gives way to a rock thought by Lopez (10, p. 683) to be intensely albitized, but which, according to the list of mineral compositions, is lower in albite than the propylitized porphyry and significantly higher in orthoclase. The nature of this rock is obscure. Associated with this rock and also in the deposit are altered rocks rich in sericite and quartz that contain orthoclase in amounts equal to, or less than, that in the unaltered rock. To judge by the analyses, other minerals must also be present. For example, in three analyses of the sericite-quartz rocks the Fe_2O_3 plus FeO plus MgO content ranges from 1.58 to 2.73 percent, yet there are no iron or magnesium minerals reported.

From the data given, I am uncertain whether the chief alteration is argillic or potassium silicate, or both.

Bingham, Utah.—Stringham (20) in a comprehensive study of the hydrothermal alteration at Bingham recognized seven stages, based on microscopic and field relations. Of the seven stages, the first four constitute the hydrothermal alteration. The critical minerals for these alteration phases are as follows: stage 1—illite and kaolinite, stage 2—hydrothermal biotite and sericite, stage 3—hydrothermal biotite and chlorite, and stage 4—quartz and sericite. Butler and others (3, p. 164) present analyses of "biotitized" and "orthoclasized" quartz monzonite from the Bingham district.

Butler's data, although meagre, indicate that locally at least potassium silicate alteration occurs, since secondary K-feldspar and biotite are critical mineral phases for this alteration facies. Stringham's data are difficult to interpret on the basis of argillic and potassium alteration facies. Stage 1 (illite and kaolinite) would be in the argillic facies, stage 2 (hydrothermal biotite and sericite) would be in the potassium silicate facies, stage 3 (hydrothermal biotite and chlorite) fits neither facies, and stage 4 (quartz and sericite) could be in either facies. It seems likely that both facies occur, and in part at least the potassium silicate follows an argillic alteration. But the entire alteration history apparently is much more complex.

Castle Dome, Arizona.—Peterson, Gilbert, and Quick (14) recognized three alteration phases in the mineralized quartz monzonite porphyry at Castle Dome; in order of increasing intensity of alteration they are propylitic, argillic, and quartz-sericite alterations. The propylitic alteration is marginal to the ore zone and decreases in intensity away from it; the argillic alteration is strongest and occurs in the ore zone; and the quartz-sericite alteration, largely enclosed by the argillic alteration, forms an inner zone superimposed on the argillic alteration.

The propylitic alteration is typical; the chief constituents are pyrite, chlorite, epidote or clinozoisite, sericite, calcite, and leucoxene. Quartz, orthoclase, and apatite are not affected. In the argillic alteration, the plagioclase and locally the biotite are partly to completely replaced by a montmorillonite-type clay in which the exchangeable base is calcium. Quartz and orthoclase are unaltered except where the argillic alteration is most intense; here both

are partly replaced by clay. Plagioclase is the least stable mineral, but the argillized plagioclase phenocrysts are sufficiently distinct to retain a relict porphyritic texture. The quartz-sericite alteration consists of numerous small veinlets composed of quartz, sericite, and a little pyrite and adularia. The veinlets comprise a central part of quartz and pyrite bordered by glistening sericitized rock in which the original textures and structures are obliterated. Locally quartz and orthoclase as well as the more susceptible plagioclase and biotite are replaced by sericite. Thus even though the veinlets carry minor adularia, both biotite and original orthoclase are unstable and the quartz-sericite alteration therefore probably is a phase of the argillic alteration, as used here.

Santa Rita, New Mexico.—Kerr and others (7) recognized four stages in the progressive hydrothermal alteration at Santa Rita. During early alteration, plagioclase phenocrysts are "cloudy" (partly sericitized and kaolinized), biotite is commonly chloritized, and clay is in scattered patches.

The orthoclase, which is in the groundmass, remains relatively fresh long after the phenocrystic plagioclase is argillized. The orthoclase is associated with primary and secondary quartz.

With increase in the intensity of alteration, the plagioclase phenocrysts are completely altered to sericite, kaolinite, and secondary quartz, and the biotite phenocrysts to "hydromica." The groundmass, too, is completely reconstituted; the quartz is recrystallized and the orthoclase and biotite are destroyed. In place of them, secondary quartz, sericite, kaolinite, hydromica, and limonite forms (7, p. 322).

The most intense alteration is silicification, which in the most intensely silicified zones destroys all the original textures and structures. The quartz occurs both in veinlets and in disseminated granules.

Part of the early alteration—the chloritization of the biotite and the clouding of the plagioclase phenocrysts—appears to be propylitic, but the later stages during which the kaolinization and sericitization were prominent is certainly argillic. The mention by Kerr and others (7, p. 319) of biotite veins and of solution and redeposition of the biotite in the groundmass suggests local potassium silicate alteration. Secondary biotite is prominently associated with secondary K-feldspar at Ajo, Ely, Bingham, and Bagdad where there is no argillic alteration.

Morenci, Arizona.—From Lindgren's (9) description, the alteration of the porphyry at Morenci is to sericite, pyrite, and quartz; apparently the alteration is pervasive. Kaolin is mentioned in the description of one of the analyzed specimens, but the description does not make it clear whether the kaolin is hydrothermal or due to acid leaching resulting from oxidation of pyrite at the surface.

Since sericite occurs in both the argillic and potassium silicate alteration facies, alone it cannot be used to distinguish one from the other. The AKF diagrams described later in the article, however, strongly suggest that it is argillic.

PHASE RELATIONS OF THE HYDROTHERMAL ALTERATION

Goldschmidt (5) first pointed out that the phase rule could be applied to metamorphic rocks in which the mineral phases were in equilibrium. The phase rule can be written as follows:

$$P + V = C + 2,$$

P is the number of phases; V is the variance or the number of degrees of freedom, such as pressure, temperature, and concentration of each phase; and C is the number of components. Goldschmidt reasoned that any common metamorphic rock must be stable over a range in both temperature and pressure, otherwise it would not occur commonly. In such a metamorphic assemblage, the variance is at least 2, and consequently P equals C; that is, the maximum number of mineral phases in equilibrium equals the number of components; this is Goldschmidt's mineralogical phase rule. Its application is qualitative rather than quantitative.

In the decision of what components are necessary to a given metamorphic assemblage, one must distinguish between those that occur in a single phase from those that occur in two or more phases. The latter components are the diagnostic ones. This does not imply that the components occurring in a single mineral phase are not significant, or that the minerals in which they occur are unstable, but only that the components, and therefore the minerals, are not critical in the distinction of one metamorphic facies or assemblage from another. For example, within the hydrothermal alteration zones, rutile appears to be the common stable form of TiO_2 (relict sphene occurs associated with rutile, but it is probably unstable or metastable); Na_2O occurs only in albite (excluding for the sake of simplicity Na_2O that may be in the clays or mica); $CuFeS_2$ occurs only in chalcopyrite; and FeS_2 only in pyrite (FeS_2 is not considered to be a component of chalcopyrite). One can also exclude from the critical or diagnostic components those that are so abundant they always occur as phases under equilibrium conditions. For example, in the alteration zones of porphyry copper deposits, SiO_2 always occurs in excess, and quartz is always present. H_2O, like SiO_2, may also be excluded because under hydrothermal conditions, aqueous solution or vapor is also a phase under the equilibrium conditions.

The critical components are those that may occur in two or more mineral phases within the temperature and pressure stability range of the metamorphic assemblage under consideration. When such components are limited to no more than three, the mineral facies in which they occur can be shown on a triangular diagram in which the three critical components occupy the apices of the diagram.

The hydrothermal alteration in the porphyry copper deposits can be elucidated by two such diagrams (ACF and AKF diagrams [3]) both of which have been used extensively for other types of metamorphic rocks. The ACF dia-

[3] Molecular percents rather than weight percents are plotted on the diagrams.

gram (Fig. 1) is applicable to the propylitic alteration. The critical components are Al_2O_3, CaO, and (FeO + MgO + MnO), which are represented by A, C, and F, respectively. In the argillic and potassium silicate alterations, however, CaO is commonly not a component of any stable phase, and the system is open for lime. In these alterations, the critical components are Al_2O_3, K_2O, and (FeO + MgO + MnO), which are A, K, and F, respectively. In the AKF diagrams, SiO_2 and H_2O occur in excess.

I recognize that the division of hydrothermal alteration of porphyry copper deposits into three facies is a simplification of a complex system or systems. Considerable ranges in temperature and pressure must occur, and the stability ranges of the characteristic mineral phases are only partly known. Unstable relicts occur in many of the altered rocks, and most contain metastable phases, both of which tend to vitiate the use of the diagrams. In addition, each of the facies either can be, or have been, subdivided into subfacies, and with additional data the fields of the subfacies might be defined. Despite all these disrupting factors, the use of the AKF and ACF diagrams has helped me to understand better the fundamental roles of the critical components—that is, those used in the ACF and AKF diagrams.

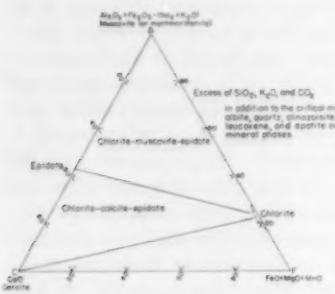

Fig. 1. Propylitic facies: ACF diagram for hydrothermally altered rocks with excess SiO_2, H_2O, and CO_2.

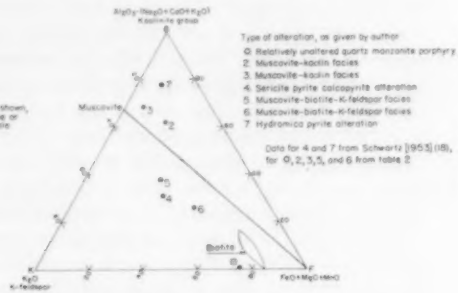
Kaolinite group
Type of alteration, as given by author
0. Relatively unaltered quartz monzonite porphyry
2. Muscovite-kaolin facies
3. Muscovite-kaolin facies
4. Sericite pyrite calcopyrite alteration
5. Muscovite-biotite-K-feldspar facies
6. Muscovite-biotite-K-feldspar facies
7. Hydromica pyrite alteration
Data for 4 and 7 from Schwartz [1955] (18), for 0, 2, 3, 5, and 6 from table 2
Muscovite
Biotite
K_2O
K-feldspar
FeO+MgO+MnO

Fig. 2. AKF diagram for hydrothermal alteration at San Manuel, Arizona. SiO_2 and H_2O in excess.

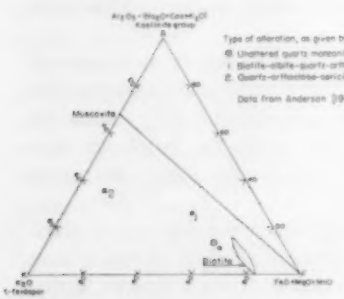

Fig. 3. AKF diagram for hydrothermal alteration at Bagdad, Arizona. SiO_2 and H_2O in excess.

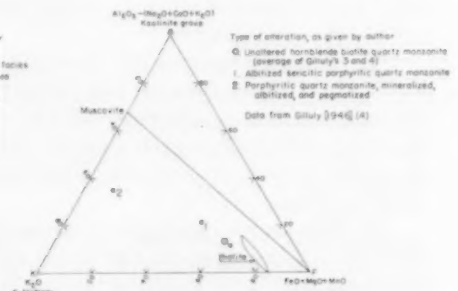
Kaolinite group
Type of alteration, as given by author
0. Unaltered hornblende biotite quartz monzonite (average of Gilluly's 3 and 4)
1. Albitized sericitic porphyritic quartz monzonite
2. Porphyritic quartz monzonite, mineralized, albitized, and pegmatized
Data from Gilluly [1946] (4)
Muscovite
Biotite
K_2O
K-feldspar
FeO+MgO+MnO

Fig. 4. AKF diagram for hydrothermal alteration at Ajo, Arizona. SiO_2 and H_2O in excess.

Propylitic Alteration.—The ACF diagram for the propylitic alteration (Fig. 1) is similar to that described by Turner and Verhoogen (22) and by Turner (21) for the muscovite-chlorite subfacies for rocks with excess SiO_2 and CO_2 (carbonate), with several exceptions. When the concentration of potassium ions is sufficiently low, montmorillonite apparently can substitute for muscovite, and magnesite, chloritoid, and stilpnomelane apparently do not occur. Montmorillonite-illite mixed-layer minerals have been recognized for some time by the clay mineralogists, so that this substitution has been adequately demonstrated. The position of montmorillonite in the alteration is considered on a later page. The critical mineral assemblages are shown on Figure 1, and in addition albite, quartz, clinozoisite, sphene or leucoxene, and apatite are stable mineral phases. K-feldspar also occurs, but it may be metastable.

Propylitic alteration is the weakest alteration recognized in the porphyry copper deposits. It forms the transition to unaltered rock, and in some deposits extends outward for at least a mile from the deposit. Propylitic alteration occurs at San Manuel, Arizona (Creasey, report in preparation); Castle

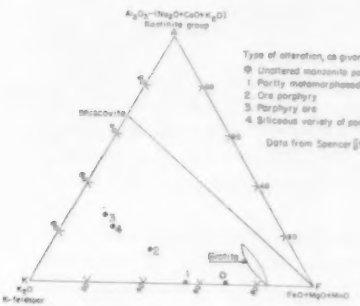

Fig. 5. AKF diagram for hydrothermal alteration at Ely, Nevada. SiO_2 and H_2O in excess.

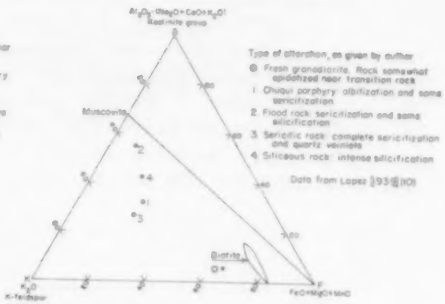
Kaolinite group
Muscovite
Biotite
K-feldspar
Type of alteration, as given by author
0. Fresh granodiorite. Rock somewhat epidotized near transition rock
1. Chuqui porphyry: albitization and some sericitization
2. Flood rock: sericitization and some silicification
3. Sericitic rock: complete sericitization and quartz veinlets
4. Siliceous rock: intense silicification
Data from Lopez [93] (10)

Fig. 6. AKF diagram for hydrothermal alteration at Chuquicamata, Chile, S. A. SiO_2 and H_2O in excess.

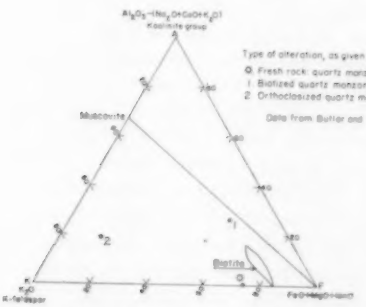

Fig. 7. AKF diagram for hydrothermal alteration at Bingham, Utah. SiO_2 and H_2O in excess.

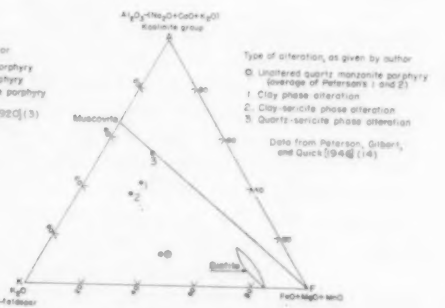
Kaolinite group
Muscovite
Biotite
K-feldspar
Type of alteration, as given by author
0. Unaltered quartz monzonite porphyry (average of Petersen's 1 and 2)
1. Clay phase alteration
2. Clay-sericite phase alteration
3. Quartz-sericite phase alteration
Data from Peterson, Gilbert, and Quick [94] (14)

Fig. 8. AFK diagram for hydrothermal alteration at Castle Dome, Arizona. SiO_2 and H_2O in excess.

Dome, Arizona (14, p. 826); Butte, Montana (15, p. 8); Santa Rita, New Mexico (7, p. 310–314); Silver Bell (6, p. 466); Ely, Nevada (19, p. 56); Chuquicamata, Chile (10, p. 680); and possibly Ajo, Arizona (4, p. 75–76), although the relations at Ajo are not conclusive.

Although propylitic alteration has been recognized, too few analyses are available to give any concept of their distribution on the ACF diagram. Perhaps when it is generally accepted as a "fringe" alteration peripheral to ore deposits more will be done to determine the chemical changes.

Potassium Silicate and Argillic Alterations.—Near the deposits, the propylitic alteration passes into the argillic and potassium silicate alterations more typically associated with ore deposits in which the rock is commonly bleached white and locally streaked and spotted with iron oxide derived from oxidized sulfides. These types of alterations are particularly clarified by use of the AKF diagrams, Figures 2 to 10. The diagnostic minerals are kaolinite and muscovite for the argillic, and muscovite, K-feldspar, and biotite for the potassium silicate alteration. In addition, rutile, apatite, pyrite, chalcopyrite, montmorillonite (substitute for muscovite), and quartz are stable mineral

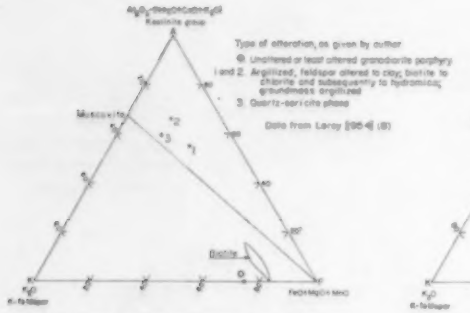
Kaolinite group
Type of alteration, as given by author
0. Unaltered or least altered granodiorite porphyry
1 and 2. Argillized, feldspar altered to clay, biotite to chlorite and subsequently to hydromica; groundmass argillized
3. Quartz-sericite phase
Data from Lacy [1954] (8)
Muscovite
Biotite
K-feldspar

Fig. 9. AKF diagram for hydrothermal alteration at Santa Rita, New Mexico. SiO_2 and H_2O in excess.

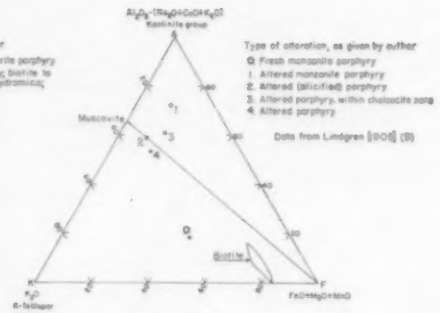

Fig. 10. AKF diagram for hydrothermal alteration at Morenci, Arizona. SiO_2 and H_2O in excess.

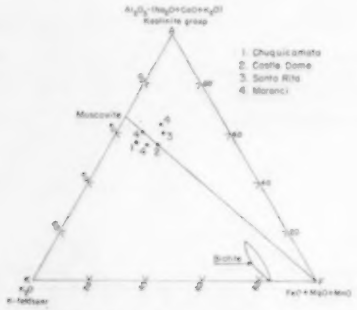

Fig. 11. AFK diagram for sericitic alteration at Chuquicamata, Castle Dome, Santa Rita, and Morenci. SiO_2 and H_2O in excess.

phases. Albite occurs locally as an unstable or metastable phase, and lesser amounts of unstable chlorite also occur. Montmorillonite probably does not occur where potassium ion is in excess, as noted later.

From the AKF diagrams, it is apparent that kaolinite, muscovite, and K-feldspar cannot coexist in equilibrium because three phases cannot be in equilibrium with two components over a temperature and pressure range. It seems likely therefore that a join exists from muscovite to some point, such as F, and that two alteration facies exist: one characterized by kaolinite and muscovite, and the other by muscovite, hydrothermal or residual K-feldspar, and biotite. All of the porphyry copper deposits contain either one or both of these alteration facies, and the difference between them appears to be a major difference in their alteration.

In some deposits, such as Castle Dome, the occurrence of much montmorillonite-type clay forms the basis for further subdivision.

Figures 2 to 10 are the AKF diagrams for the nine porphyry copper deposits, and the mineral phases present are tabulated (Table 1). Each deposit is plotted on a separate diagram, and each diagram contains a plot for the fresh rock as well as one for each of the hydrothermally altered equivalents. The plot of the unaltered rock serves as a starting point to show the path of the change in relative amounts of the components on the diagram. They are especially helpful where equilibrium conditions have not been reached, for they show the extent to which the composition has changed as the result of the incomplete change from unstable to stable minerals. The numerical sequence for individual deposits does not necessarily indicate increasing intensity of alteration. Each plot was numbered so it could be keyed to the list of minerals present (Table 1) and to the gain and loss charts (Fig. 12).

Under equilibrium conditions, the plot of a rock will fall within the field indicated by the critical mineral phases present. It is well-known that all the critical mineral phases need not be present for a rock to be within a facies; the diagrams give the maximum number that can be present. For example, an altered porphyry containing muscovite and K-feldspar is in the muscovite-biotite-K-feldspar facies, and it will plot between muscovite and K-feldspar near the A-K side of the diagram.

The two facies indicated in the AKF diagrams agree surprisingly well with the actual mineral phases present, and in most of the deposits the analyses indicate that equilibrium conditions were approached. That is, in most diagrams the plot of the analyses falls within the facies indicated by the mineral phases present. There are exceptions, of course, such as Castle Dome (Fig. 8). Lack of equilibrium is recorded by metastable minerals, such as K-feldspar in the muscovite-kaolinite facies, and albite. Most workers have recognized that K-feldspar persists long after the plagioclase has been completely argillized. Unstable relict carbonate can also be a disturbing factor; it tends to move the plot toward the muscovite-biotite-K-feldspar field.

Apparently the muscovite-kaolinite facies is the argillic alteration described by Lovering and others (12). Only argillic alteration occurs in the "por-

Table 1: Principal mineral composition of the rocks whose chemical composition are listed in Table 2.

	San Manuel, Arizona							Hayden, Arizona			Ajo, Arizona			Ely, Nevada					Chuquicamata, Chile, S. A.					Bingham, Utah			Castle Dome, Arizona				Santa Rita, New Mexico				Morenci, Arizona				
	•	7	1	?	3	4	5	6	•	1	2	•	1	2	•	1	2	3	4	•	1	2	3	4	•	1	2	•	1	2	3	•	1	2	3	•	1	2	3	4
Quartz	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
K-Feldspar	X		X			X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X		X	X			X				
Albite		X	X			X	X	X		X	X		X					X	X		X								X	X	X								
Plagioclase	35©								X			X			54©	83©				74©					79©	77©	81©	77©				30±©	X			82©				
Muscovite				X	X	X	X	X		X	X		X			X	X	X	X		X	X	X	X	X	X	X		X	X	X		X	X	X	X	X	X	X
Biotite	X						X	X	X	X		X		X		X	X	X	X	X					X	X	X	X		X		X	X						
Hornblende	X								X			X			X	X[2]															X	X							
Kaolin		X	X	X	X											X				X	X	X	X	X				X				X	X	X		X				
Chlorite	X		X			X							X	X		X				X	X	X	X									X				X				
Augite																									X															
Serpentine																																				X		X	X
Pyrite		X	X	X	X	X	X	X								X		X	X			X							X	X	X		X	X	X	X			
Chalcopyrite						X	X	X									X	X	X																	X			
Alunite		X																															X	X					
Hyiruuion		X	X																														X	X					
Magnetite															X																X								
Beidellite																													X	X									

© Ab. content
? Hornblende, chlorite, epidote, and biotite
• Unaltered rock

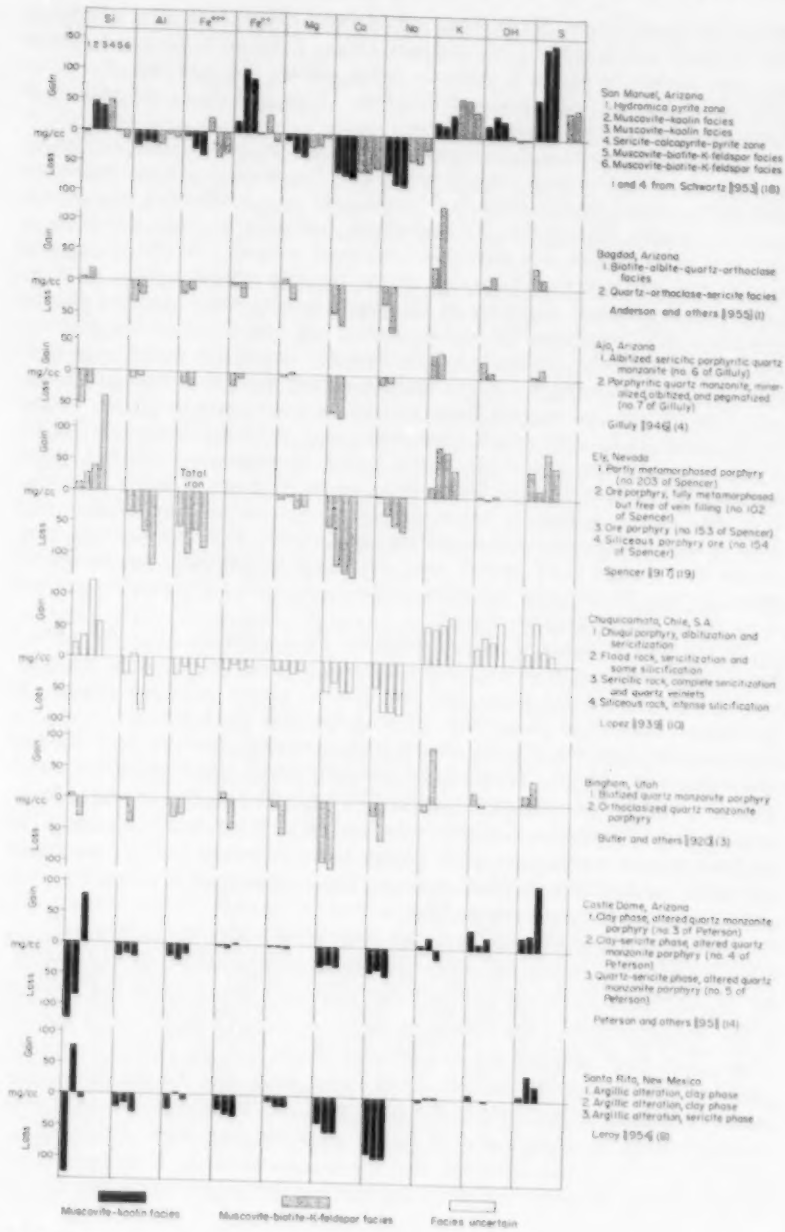
Si
Al
Fe^{+++}
Fe^{++}
Mg
Ca
Na
K
OH
S
123456
Gain
Loss
mg/cc
Total iron
San Manuel, Arizona
1. Hydromica pyrite zone
2. Muscovite–kaolin facies
3. Muscovite–kaolin facies
4. Sericite–calcopyrite–pyrite zone
5. Muscovite-biotite-K-feldspar facies
6. Muscovite-biotite-K-feldspar facies
1 and 4 from Schwartz [955] (18)
Bagdad, Arizona
1. Biotite-albite-quartz-orthoclase facies
2. Quartz–orthoclase–sericite facies
Anderson and others [955] (1)
Ajo, Arizona
1. Albitized sericitic porphyritic quartz monzonite (no. 6 of Gilluly)
2. Porphyritic quartz monzonite, mineralized, albitized, and pegmatized (no. 7 of Gilluly)
Gilluly [946] (4)
Ely, Nevada
1. Partly metamorphosed porphyry (no. 203 of Spencer)
2. Ore porphyry, fully metamorphosed but free of vein filling (no. 102 of Spencer)
3. Ore porphyry (no. 153 of Spencer)
4. Siliceous porphyry ore (no. 154 of Spencer)
Spencer [917] (19)
Chuquicamata, Chile, S.A.
1. Chuqui porphyry, albitization and sericitization
2. Flood rock, sericitization and some silicification
3. Sericitic rock, complete sericitization and quartz veinlets
4. Siliceous rock, intense silicification
Lopez [935] (10)
Bingham, Utah
1. Biotized quartz monzonite porphyry
2. Orthoclasized quartz monzonite porphyry
Butler and others [920] (3)
Castle Dome, Arizona
1. Clay phase, altered quartz monzonite porphyry (no. 3 of Peterson)
2. Clay-sericite phase, altered quartz monzonite porphyry (no. 4 of Peterson)
3. Quartz-sericite phase, altered quartz monzonite porphyry (no. 5 of Peterson)
Peterson and others [955] (14)
Santa Rita, New Mexico
1. Argillic alteration, clay phase
2. Argillic alteration, clay phase
3. Argillic alteration, sericite phase
Leroy [954] (8)
Muscovite–kaolin facies
Muscovite-biotite-K-feldspar facies
Facies uncertain

FIG. 18. Gain and loss charts for eight porphyry copper deposits.

phyry" at Castle Dome, Santa Rita, and Morenci (Figs. 8, 9, 10), whereas at San Manuel and possibly Chuquicamata (Figs. 2, 6) both the argillic facies and the muscovite-biotite-K-feldspar facies occur. In contrast the "porphyries" at Bagdad, Ajo, Ely, and Bingham (Figs. 3, 4, 5, 7) are entirely in the muscovite-biotite-K-feldspar facies.

Lack of equilibrium is most apparent in the Castle Dome deposit, (Fig. 8). In both the clay (montmorillonite-type) and clay-sericite phases, orthoclase and partly altered biotite (bleached biotite) persist. Orthoclase was able to exist metastably throughout the clay phase, although a slight alteration to clay was noted where this alteration was most intense. Biotite is bleached locally, and partly replaced by clay where the clay alteration was most intense. Both minerals disappear in the quartz-sericite phase, and the plot for this phase falls very near the line separating the two facies on the diagram. To judge by the relict biotite and orthoclase, the clay phase would seem to be a weak argillic alteration. Some sericite occurs with the montmorillonite-type clay, but the clay entirely disappears in the quartz-sericite phase. Yoder and Eugster (23) synthesized muscovite using montmorillonite plus $K_2O \cdot Al_2O_3$ plus kaolinite plus water at the lowest temperature attempted, which was 400° C at $15 \times 10^{+3}$ psi water pressure in 90 hours. Noll (13), however, was able to synthesize either clay or mica in an alkaline solution with K_2O at constant temperature depending on the ratio of the components used. Hence the change from partial clay alteration to complete quartz-sericite alteration can be effected by altering the component concentration as well as by temperature-pressure change.

Of the four analyses of altered rocks for Chuquicamata (Fig. 6), plots 1 and 2 agree reasonably well with the mineral phases. Plot 1 is in the muscovite-biotite-K-feldspar facies and the mineral phases show an increase in K-feldspar from 10 to 27 percent. Plot 2 lies near the boundary separating the two facies, and the mineral phases show a marked decrease in K-feldspar and increase in sericite. Both plots 3 (sericitic rock) and 4 (siliceous rock), however, are in the muscovite-biotite-K-feldspar facies, but mineral phases and the rock descriptions indicate they are part of the argillic facies. The analyses of both contain too much potash to be accounted for by the sericite and small amount of orthoclase reported, hence agreement between the plots and the mineral phases is not possible.

The AKF diagram for San Manuel (Fig. 2) is one of the most interesting because both alteration facies occur and are sharply separated in the deposit: the argillic facies forms the hanging wall and most, if not all, of the footwall of the deposit, whereas the muscovite-biotite-K-feldspar facies forms the ore zone. The AKF diagram for San Manuel shows that the direction of compositional change for the argillic facies varies from that for the muscovite-biotite-K-feldspar facies. From the field relations, the alterations could have occurred either simultaneously or in the sequence potassium silicate to argillic facies. It is clear, however, that the muscovite-biotite-K-feldspar facies did not develop from the argillic facies, because the argillic facies has lost all

vestige of the original texture and structures, whereas the muscovite-biotite-K-feldspar facies still retains a good relict porphyritic texture.

The AKF diagrams for Bagdad, Ajo, and Ely (Figs. 3, 4, 5) are straightforward and self-explanatory. Plot 1 (biotitized rock) for Bingham (Fig. 7) is interesting because the critical phases are muscovite and biotite and the plot on the diagram lies on the imaginary join between muscovite and biotite. The AKF diagrams for Santa Rita and Morenci (Figs. 9, 10) neatly show the development of the argillic facies only. It is interesting to note that the original composition of the "porphyry" at Santa Rita changed more than that at Morenci.

The careful work of those studying the alteration of the porphyry copper deposits has shown that significant differences occur within the fields of the two facies. This is illustrated by more than one plot within a facies. Each plot represents a consistent variation which could be recognized, and in some places, mapped. The AKF diagrams for Bagdad and Bingham illustrate this point; in both deposits the investigators distinguished between predominantly biotitic alteration and predominantly K-feldspar alteration. When sufficient information of this type is available, perhaps fields for subfacies will be defined. Perhaps the first of these will be a simple sericite subfacies because of the widespread occurrence of quartz-sericite alteration. Figure 11 shows the plots for quartz-sericite alteration from Chuquicamata (plot 2 only), Castle Dome, Santa Rita, and Morenci.

Some investigators have pointed out mineral phases or associations that apparently are not in accord with the assemblages in equilibrium indicated by the AKF diagrams. Gilluly (4, p. 75) reports that chlorite occurs along with biotite, yet the alteration at Ajo is in the muscovite-biotite-K-feldspar facies. Similarly, Sales and Meyer, 15, p. 11) report regeneration of biotite from chlorite in the kaolinite subzone at Butte, and Leroy (8, p. 750) noted secondary biotite in the argillic alteration at Santa Rita. Peterson and others (14, p. 834–835) also reported the recrystallization of biotite at Castle Dome where the alteration is entirely argillic, but they suggest that it is a metamorphic effect produced by intrusion of granite porphyry near the quartz monzonite. On the basis of the simple three component system used, the writer has no explanation for these seemingly anomalous relations. They may therefore be the consequence of over simplification of a more complex system.

The role of montmorillonite-type clay is difficult to evaluate. Sales and Meyer (15, p. 8–9) describe montmorillonite associated with the alteration of biotite to chlorite, and of hornblende to chlorite, carbonate, and minor epidote in their montmorillonite subzone. This indicates that montmorillonite is part of what is here called propylitic alteration. In contrast, at Castle Dome chlorite and carbonate are unstable in the zone where the plagioclase is intensely altered to montmorillonite-type clay, in which the exchangeable base is calcium (14, p. 829). Perhaps the solution is in the ubiquitous occurrence of muscovite;[4] it is one of the critical minerals (1) in the propylitic alteration,

[4] Perhaps it is not the muscovite that is the critical feature, but rather the basic 3-layer silicate structure.

(2) in the argillic facies, and (3) in the muscovite-biotite-K-feldspar facies. Possibly montmorillonite can substitute for muscovite in the first two, but not the last one. At least, it has not yet been reported in the muscovite-biotite-K-feldspar facies. Perhaps here the concentration of potassium ion is too high. Noll (13) synthesized montmorillonite and kaolinite at 300° C and 87 atm. pressure (H_2O constant) using the molecular ratio of $K_2O : Al_2O_3 : SiO_2$ of 0.2 : 1 : 4, but obtained only mica when the ratio was changed to 0.37 : 1 : 2. As pointed out elsewhere, the analyses of the muscovite-biotite-K-feldspar facies average about 60 percent higher in potassium than do those of the argillic facies.

CHEMICAL DATA

Since Anderson's (1) studies on the altered rocks at Bagdad, Castle Dome, Ajo, and Ely, chemical analyses of altered and fresh rocks have become available for San Manuel (18, Table 2) and Santa Rita (8). In addition, analyses are available for Chuquicamata (10). It seems appropriate therefore to present all current information on gains and losses of the chemical constituents of altered and fresh rocks. To give a visual picture of the mineralogic changes, the mineral phases for each analyzed specimen are listed in Table 1, and the chemical analyses from which the calculations were made in Table 2.

The gain and loss charts for individual deposits are on Figure 12, and the overall gains and losses of the different elements are listed in Table 3. This tabulation gives equal weight to each analysis, and attempts to average the losses and gains for all types of alteration. Each analysis, however, represents a type of alteration, as determined by the investigator. Possibly the Table does show the gross gains and losses of the hydrothermal alteration of porphyry coppers as a whole, and this is all that the table is intended to show. The gain of 1.2 percent or 9 mg/cc of Si per sample undoubtedly has no significance, but the nearly consistent loss of Al, even though it is only 10½ percent, probably is significant. Despite the alteration from minerals lower in aluminum to those higher, such as the alteration of feldspar to sericite and clay minerals, the general decrease in density of the rock as a result of a general leaching of the original silicate minerals accounts for the general loss of aluminum for the rock as a whole.

In general, analyses of the altered rocks show a moderate loss in iron and magnesium. That remaining occurs in several different minerals. Some of the least altered rocks contain chlorite as a stable or metastable mineral, and hydrothermal biotite occurs in the muscovite-biotite-K-feldspar facies. Iron also is sulfidized to form pyrite, and some is converted to chalcopyrite; this iron could reasonably have come entirely from the breakdown of the original mafic constituents. Certainly all the original mafic minerals, even the original biotite, are unstable in the zone of hydrothermal alteration, and during the transformation to other minerals, some iron and magnesium is lost.

The general loss in calcium is widely accepted, and needs little comment. Except in the propylitic alteration, the system is open for calcium, and the loss is proportional to the intensity of the alteration. The average loss in elemental calcium for the 8 deposits is 64 mg/cc or 84 percent. Sodium is

leached, and in this respect it is similar to calcium. In contrast, potassium, hydroxl ion (water), and sulfur are added, and in all deposits the relative gain in sulfur is large.

Table 2: Chemical analyses from nine porphyry copper deposits. Principal minerals in each rock analyzed are listed in Table 1.

The gain and loss charts (Fig. 12) are derived from these analyses.

	San Manuel, Arizona								Bagdad, Arizona			Ajo, Arizona		
	*	7	1	2	3	4	5	6	*	1	2	*①	1	2
SiO_2	61.8	65.64	64.09	62.7	63.6	66.98	64.8	62.6	64.49	67.26	68.61	66.23	66.92	65.57
Al_2O_3	16.5	15.95	15.50	15.2	16.8	15.32	17.0	16.4	17.43	15.89	16.57	15.71	15.78	15.42
Fe_2O_3	3.3	6.41	2.98	1.4	0.43	1.87	0.54	1.0	1.84	0.88	1.16	2.20	1.30	1.05
FeO	1.2	0.48		1.1	0.1	1.13	0.8	1.2	1.65	1.44	0.53	1.98	1.08	2.40
MgO	2.6	0.28	2.03	0.68	0.41	1.33	1.4	2.4	1.93	2.30	0.43	1.58	1.40	1.66
CaO	3.6	0.27	0.53	0.22	0.10	0.50	0.57	1.0	3.47	1.18	0.16	3.78	0.76	0.39
Na_2O	4.3	0.72	1.36	0.24	0.19	2.33	2.2	3.2	4.48	3.10	0.78	3.89	3.46	3.33
K_2O	2.5	1.95	3.69	3.2	4.1	5.29	5.4	4.5	2.38	3.94	8.37	3.22	5.26	5.01
H_2O+	1.9	4.58	2.76	3.2	3.0	2.15	1.9	1.9	0.90	1.07	1.66	0.67	1.92	1.06
H_2O-	0.5	0.34	0.49			0.46			0.44	0.23	0.14	0.03	0.71	0.79
TiO_2	0.65	0.48	0.73	0.71	0.48	0.60	0.57	0.61	0.66	0.37	0.32	0.47	0.56	0.36
P_2O_5	0.22	0.22	0.28	0.24	0.17	0.20	0.25	0.24	0.19	0.17	0.13	0.24	0.28	0.23
CO_2	1.0	0	0			0			0.12	0.04	0.06			0.41
MnO	0.10	0.008	0.02	0	0	0.04	0	0	0.09	.04	none	0.08	0.05	0.03
CuO		0.038	0.33			1.10				1.05				
NaO													0.11	0.05
SO_3		2.00	0			0.04					1.10		0.30	
S						0				1.35				0.58
FeS_2			4.62	9.9	10.3	-	3.2	3.56						0.80
$CuFeS_2$														1.00
Cu														
Cu_2S														
O=S				-2.0	-2.1		-0.6	-0.7		-0.68				
						99.34			99.87	99.63	99.82	100.08	99.92	99.72
Blk Sp.Gr.	2.625		2.52	2.74	2.69	2.58	2.80	2.55	2.7	2.6	2.6	2.7	2.5	2.65
Powd.Sp.Gr.		2.71	2.76	2.84	2.84	2.64	2.70	2.78	2.75	2.65	2.68			

*Unaltered rock; ① No. 4 of Gilluly; ② Average of analyses no. 1 and 2 of Peterson; ③ Values uncertain; ④ Approximate; ⑤ $AsFe_2O_3$.

San Manuel: Analyses 1, 4, and 7 after Schwartz (18), analyses *, 2, 3, 5, and 6 unpublished. Analysts for * Paul L. D. Elmore, Katrina E. White, and Samuel D. Botts. Analysts for 2, 3, 5, and 6 Paul L. D. Elmore and Samuel D. Botts, U. S. Geological Survey.

Bagdad: Anderson (1)

Ajo: Gilluly (4)

Table 2—Continued

	Castle Dome, Arizona				Santa Rita, New Mexico				Morenci, Arizona				
	*[1]	1	2	3	*	1	2	3	*	1	2	3	4
SiO_2	70.14	69.89	70.33	72.15	64.87	64.58	70.14	68.75	68.04	46.67	69.55	64.88	72.78
Al_2O_3	13.90	14.33	14.53	11.77	16.63	17.82	14.86	15.38	17.20	20.92	16.43	16.41	15.35
Fe_2O_3	1.93	1.03	0.50	1.00	2.36	1.16	2.36	2.03	0.34	0.37[2]	0.86[4]	0.65[3]	0.55
FeO	1.99	0.99	1.03	0.96	2.35	1.14	0.66	0.57	0.67	0.36[3]	0.11[4]		0.10
MgO	0.65	0.73	0.59	0.43	2.27	1.93	1.08	1.16	1.05	0.85	0.62	1.12	0.89
CaO	1.87	0.25	0.32	0.23	3.24	0.93	0.05	0.05	2.21	0.15	0.15	0.11	0.14
Na_2O	2.65	0.72	1.02	0.28	5.71	0.76	0.14	0.14	5.33	0.16	0.17	0.12	0.36
K_2O	4.52	5.53	6.10	3.46	2.79	3.11	2.77	3.97	2.65	4.33	5.05	4.96	5.00
H_2O+	1.13	2.81	1.76	1.82	0.15	0.74	0.15	0.10	1.73	5.01	2.69	2.74	3.22
H_2O-	0.14	1.75	1.08	0.02					0.60	0.94	1.00	0.83	1.21
TiO_2	0.59	0.66	0.51	0.43					0.41	0.43	0.41	0.38	0.45
P_2O_5	0.71	0.13	0.13	0.08					0.12	0.15	0.05	0.12	0.05
CO_2					0.08	0.04	0.05	0.03	0	0	0	0	0
MnO	0.12	0.01	0.02	0.01					0.06	0	0	tr.	0
CuO													
BaO									0.10	0.04	0.05	0.07	0.02
SO_3									0	0.18	0.10	0.10	0.08
S					0.22	0.62	1.86	1.35					
FeS_2	0.04	1.72	1.76	7.05					0.24	19.18	3.09	4.96	0.06
$CuFeS_2$													
Cu					0.07	0.15	0.71	0.92					
Cu_2S									0.02	0.24	0.07	2.42	-
CuS													
	99.88	99.86	99.68	99.69	100.74	93.98	94.83	94.45	100.34	99.98	100	99.87	100.26
Bulk Sp.Gr.	2.65	2.3	2.3	2.8	2.36	1.94	2.41	2.20					
Powd. Sp.Gr.	2.81	2.69	2.60	2.99									

Castle Dome: Peterson and others (14)

Santa Rita: Le Roy (8)

Morenci: Lindgren (9)

Some of these overall averages, however, can be misleading. For example, the AKF diagrams illustrate the compositional shift toward A for the argillic facies, and toward K for the muscovite-biotite-K-feldspar facies. Excluding Chuquicamata because of the uncertainty of which alteration facies is represented, the altered rocks in the argillic facies gained an average of about 8 mg/cc (15% increase) potassium, whereas those in the muscovite-biotite-K-feldspar facies gained about 51 mg/cc (76% increase). In the San Manuel

Table 2—Continued

	Ely, Nevada					Chuquicamata, Chile, S. A.					Bingham, Utah		
	*	1	2	3	4	*	1	2	3	4	*	1	2
SiO_2	57.48	60.37	64.11	64.73	74.62	66.92	70.40	66.98	76.55	70.15	58.64	63.09	66.27
Al_2O_3	17.85	15.96	16.52	14.41	10.73	16.08	14.53	15.86	10.21	14.07	15.35	16.33	15.01
Fe_2O_3	3.40	0.51	0.41		0	1.38	tr.	0.63	tr.	0.67	3.25	1.37	1.84
FeO	3.46	1.80	1.07	Fe=2.89	Fe=1.94	2.22	1.36	0.37	1.60	1.27	2.54	3.29	0.39
MgO	2.02	1.63	1.85	0.76	0.83	1.44	0.33	0.35	0.18	0.35	3.84	3.53	0.71
CaO	6.60	4.12	1.40	0.44	tr.	2.93	0.56	1.18	0.64	0.63	5.37	0.70	0.18
Na_2O	3.07	3.13	1.64	0.70	0.33	4.34	2.48	0.38	0.42	0.29	3.60	2.79	0.72
K_2O	4.16	5.07	8.26	7.84	6.57	2.38	5.04	4.66	5.06	5.66	4.23	3.91	9.62
H_2O+	0.55	1.34	0.58	1.94	0.69	1.40	2.40	3.05	2.70	4.00	1.50	2.35	1.50
H_2O-	-	0.92	1.71	0.82	0.26	0.55	0.35	0.35	0.20	0.35	0.86	0.95	0.34
TiO_2	0.71	0.71	0.75	0.57	0.42	0.18	0.10	0.05	0.04	0.09	0.83	0.43	0.47
P_2O_5	0.21	0.47	0.40	0.10	0.06	0.14	tr.	-	0.14	tr.	0.02	0.42	0.16
CO_2	0.04	0.74	0.48	0	0		0				0	0	0
MnO	0.29	0.05									tr.	0	0
CuO											-	0.55	1.62
BaO	0.07	0.11		0.04	tr.						0.18	0.09	0.17
SO_3				0.22		0.07	0.86	1.14	1.13	1.34	-	0	0
S				2.83	2.01		0.30	0.34	0.27		0.05	0.67	1.66
FeS_2		3.11	0.32				0.22	3.07	0.18	0.98			
$CuFeS_2$		0.20	0.95										
Cu				1.96	1.57	-	1.10	1.29	1.11	-			
Cu_2S													
O=S											-0.02	-0.37	-0.90
	100.25		100.08	100.25	99.55	100.03	100.03	99.70	100.23	99.85	100.24	100.18	99.91
Blk Sp.Gr.	2.71	2.62	2.54	2.52	2.52	2.74	2.67	2.84	2.73	2.74	2.76	2.58	2.43
Powd. Sp.Gr.													

Ely: Spencer (19)

Chuquicamata: Lopez (10)

Bingham: Butler and others (3)

deposit where both alteration facies occur, the argillic facies shows an average increase of potassium of about 20 mg/cc (30%) compared to 60 mg/cc (90%) for the potassium silicate facies. Another example is afforded by the local stability (or metastability) of albite in the muscovite-biotite-K-feldspar facies. Here the average loss in sodium is 48 mg/cc (47%), compared to an average loss of 94 mg/cc (86%) in the argillic facies where the albite is unstable.

The hydrothermal alteration in the porphyry copper deposits appears to

TABLE 3

AVERAGE LOSSES AND GAINS OF ELEMENTS FROM EIGHT PORPHYRY COPPER DEPOSITS

	No. samples showing loss / Total no. samples	Average loss (−) or gain (+) in mg/cc/sample	Average percent loss (−) or gain (+)/sample
Si	11/26	+8	+1.0
Al	24/26	−26½	−10½
Fe^{3+}	23/24*	−25	−56
Fe^{2+}	18/24*	−5	
Mg	24/26	−15	−43
Ca	28/28	−64	−84
Na	26/26	−52	−65
K	4/26	+39	+63
OH	6/26	+17	+66
S	0/26	+45	

* Analyses giving only total iron not included.

be amenable to interpretation and illustration through AKF and ACF diagrams. Their use for other types of hydrothermal deposits, such as epithermal and mesothermal veins, may be equally helpful. Such a standard approach would be most useful in pointing out similarities and differences, and perhaps would help to point out where more information is needed.

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SULFUR ISOTOPES AND HYDROTHERMAL MINERAL DEPOSITS

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ABSTRACT

In the past, hopeful attempts have been made to determine the type of mineral deposit (i.e., pegmatitic, magmatic, hydrothermal, and so forth) by means of sulfur isotope ratios. The recognition of the overlap and similarity of S^{32}/S^{34} ratio values determined from specimens from such deposits is a clear indication that these ratios provide no simple panacea to the classification of mineral deposits.

On the other hand, however, sulfur ratios of specimens from some hydrothermal deposits, although they do not exhibit identical values, do show a comparitively narrow spread, usually $< \pm 0.5$ percent, in ratio values which is a striking contrast when compared to other hydrothermal deposits that contain sulfides that vary in ratio by as much as four percent and more.

The recognition that these rather similar hydrothermal deposits are dissimilar in degree of sulfur isotopic homogeneity is quite striking when considered in relation to the known geology of the deposits.

In those deposits that are intimately associated with the intrusive body from which it is believed the ore solutions were derived, the spread in ratio values is very narrow, but those deposits that are not associated with an apparent magmatic source exhibit a broad spread in ratio values.

As a result, it is suggested that sulfur isotope ratios may provide an additional aid or "tool" whereby the economic geologist may be better equipped to learn more about the different sources of hydrothermal solutions and obtain a better understanding about the processes by which hydrothermal mineral deposits have been formed.

It is suggested, furthermore, as an initial step that hydrothermal deposits might be subdivided according to different ore fluid sources, or, at least, according to what may be believed to be the sources. Apparently, sulfur isotope ratios do aid in providing some evidence for sub-dividing many hydrothermal deposits as *Magmatic Hydrothermal* deposits, *Metamorphic Hydrothermal* deposits, and *Ground Water Hydrothermal* deposits.

It is evident, therefore, that the use of the term *hydrothermal* in this paper includes those minerals formed by heated waters that are not at all necessarily magmatic in origin. It is believed that most students of ore genesis would not restrict the term to this sole source.

INTRODUCTION

At the rate at which knowledge about many of the specialties of different scientific fields is now accumulating, it is difficult to keep abreast of the progress made even in those specialties that have a bearing on one's own field of endeavor. The relatively recent specialty of isotope geology is having an increasingly important bearing on providing a better understanding of geo-

logical principles and processes. Yet the field of isotope geology has developed into several subspecialties; for example, radiogenic isotopic age studies and non-radiogenic isotopic abundance studies are two broad categories of this field that include numerous highly specialized but very significant topics. The results of investigations on one of these topics is the subject of this paper, which is to discuss some of the more recent results pertaining to the formation of mineral deposits obtained from studies of the variation in isotopic abundances of just one element, sulfur.

It is well recognized that studies of variations of stable isotopic ratios are no panacea to the problems of understanding the processes by which minerals become concentrated. Enough information and interesting hypotheses have arisen, however, through S^{32}/S^{34} ratio studies alone that it is deemed worthwhile to present these results and suggest some hypotheses for consideration by the students of ore genesis.

During the past, hopeful attempts have been made to distinguish by means of sulfur isotope ratios between mineral deposits classified under the categories of magmatic, hydrothermal, pegmatitic, sedimentary, and so forth. The early recognition of the overlap and similarity of S^{32}/S^{34} ratio values determined from specimens from such deposits was a clear indication that this hope would not materialize.

Instead, as more samples were analyzed, especially from just one deposit, the results appeared to be more significant. It was noted, for example, that the spread in ratio values of sedimentary sulfide samples increased as more samples were analyzed. In contrast, specimens from some hydrothermal ore deposits did not vary in S^{32}/S^{34} ratio values or if so, only over a very narrow range, whereas in other hydrothermal deposits the spread in ratios was appreciably greater.

The recognition of isotopic characteristics of different and even supposedly similar hydrothermal types of deposits is of even greater significance when studied from the viewpoint of the known geology of the deposits. As a result of these observations, suggestions have arisen pertaining to the hydrothermal processes of mineral concentration. It is the purpose of this paper to present these suggestions and attempt an analysis of the significance of these results.

ACKNOWLEDGMENTS

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Most of the results and suggestions included in this paper were presented before the geological groups of Princeton and Harvard Universities and before The Lamont Geochemical group at Columbia University. I am grateful for the constructive comments offered by these groups.

My deepest gratitude, however, is owed to Professor Alan M. Bateman

who during invaluable discussion with me has provided not only many valid reasons for the rejection of some earlier ideas but has suggested important improvements in many of the ideas herein expressed. There is, however, no implication that Professor Bateman is in total agreement with me on the feasibility of some of the ore-forming processes suggested herein.

TECHNIQUES AND PROCEDURES

Sulfate minerals were treated as follows: the soluble sulfate samples were first taken into solution, following which the sulfate was precipitated as barium sulfate by adding barium chloride in solution. The precipitate was mixed with an excess of carbon and heated to 750–800° C in order to reduce the sulfate to barium sulfide. The barium sulfide was extracted in slightly acidified cold water, and the sulfur was precipitated as lead sulfide which was then suitable for preparation of sulfur dioxide. Barite samples were first leached and purified with hot concentrated nitric acid before reduction.

The sulfide minerals were separated from the associated gangue and other ore minerals by air elutriation techniques, differential flotation using a Mayeda cell (16), and by selection of clean sulfide fragments through megascopic means and with the use of a binocular microscope. If possible, at least 0.5 gram of each sulfide sample was prepared although 100 milligrams is adequate for an isotopic analysis.

In preparation for the isotopic analysis each sulfide specimen was converted to sulfur dioxide by a standard procedure in which the sulfide was burned in a previously evacuated system at a temperature of 1,000° C in a stream of oxygen from a standard cylinder; the resulting sulfur dioxide gas was dried by being passed through phosphorous pentoxide and collected in a liquid nitrogen trap before being transferred to a sample flask. The flowage and burning rates were controlled by means of bubble-counters, mercury manometers, and time schedules. The yield and purity of several samples was determined to be satisfactory through isotopic analysis by operation of the mass spectrometer in the analytical mode, during which time a scan was made of all mass (m/e) values between 1 to 100. As a further precaution all samples were checked for purity by comparing the mass 66 amplifier output with the same peak voltage output of an equal volume of the standard sulfur dioxide gas.

The instrument used was a double collector Model 21-401 Consolidated Electrodynamics Corporation mass spectrometer. The precision of the results was obtained by a repetitive rapid comparison of the sample ratio to the ratio of a standard sulfur dioxide gas; this cyclic procedure required a minimum time of twenty-four minutes to complete an isotope analysis consisting of six alternating comparisons of each specimen with the standard gas.

For purposes of comparison with other published S^{32}/S^{34} studies, all ratios are related to the common standard of troilite from the Cañon Diablo meteorite which has an S^{32}/S^{34} ratio of 22.21, and the precision of the results is $\pm$ 0.02 in standard deviation or better.

Although S^{32}/S^{34} ratios have been reported almost without exception as ratio values, deviations from a standard expressed in permil values offer a

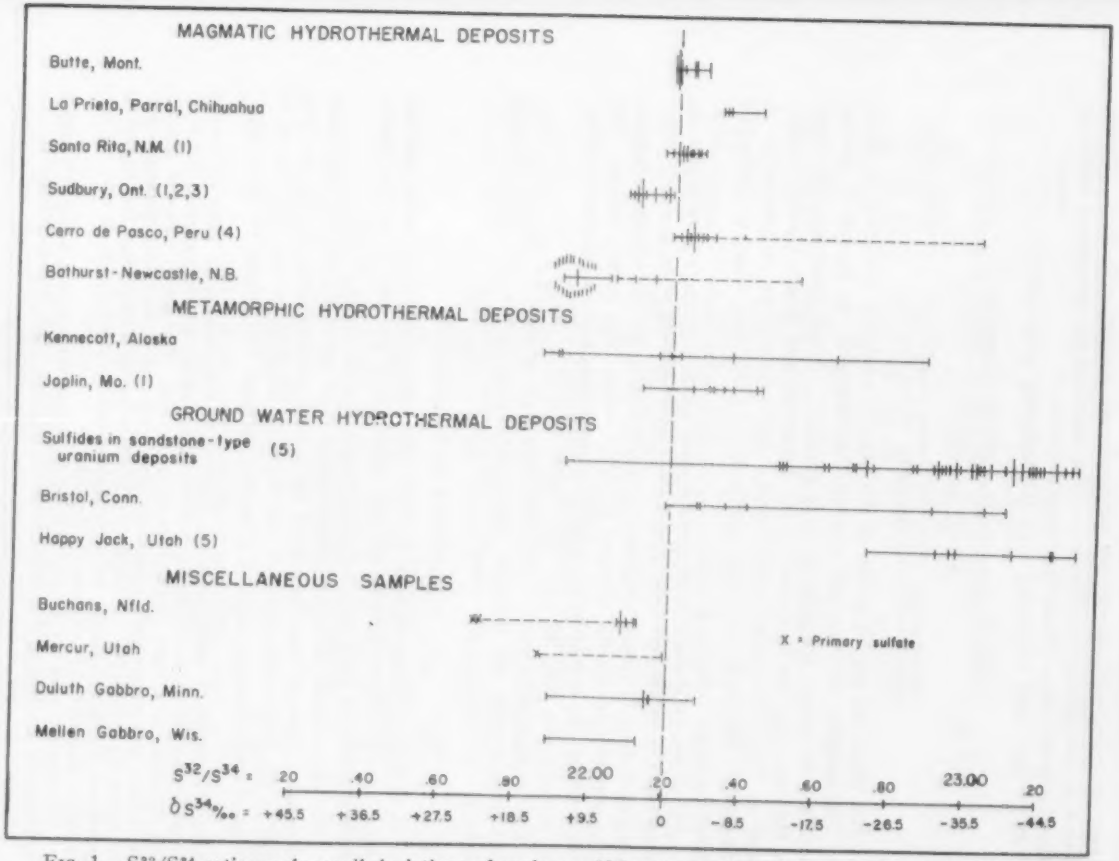
MAGMATIC HYDROTHERMAL DEPOSITS
Butte, Mont.
La Prieta, Parral, Chihuahua
Santa Rita, N.M. (1)
Sudbury, Ont. (1,2,3)
Cerro de Pasco, Peru (4)
Bathurst-Newcastle, N.B.
METAMORPHIC HYDROTHERMAL DEPOSITS
Kennecott, Alaska
Joplin, Mo. (1)
GROUND WATER HYDROTHERMAL DEPOSITS
Sulfides in sandstone-type uranium deposits (5)
Bristol, Conn.
Happy Jack, Utah (5)
MISCELLANEOUS SAMPLES
Buchans, Nfld.
Mercur, Utah
Duluth Gabbro, Minn.
Mellen Gabbro, Wis.
X = Primary sulfate
S32/S34 = .20 .40 .60 .80 22.00 .20 .40 .60 .80 23.00 .20
δ S34‰ = +45.5 +36.5 +27.5 +18.5 +9.5 0 -8.5 -17.5 -26.5 -35.5 -44.5

FIG. 1. S^{32}/S^{34} ratios and permil deviations of various sulfide minerals from different mineral deposits. Numbers in parentheses refer to references: (1) = reference 18, (2) = ref. 11, (3) = ref. 20, (4) = ref. 14, and (5) = ref. 13.

more rapid connotation of the variation of samples from the standard. These values are given with the S^{32}/S^{34} ratios of each sample on Table 1, and are plotted as the abscissa of Figure 1. The standard for the permil values is still, of course, Cañon Diablo troilite.

$\delta‰$ values were calculated from the following relationship:

$$\delta S^{34}\,{}^{0}/_{00} = \frac{S^{32}/S^{34}\ (\text{standard}) - S^{32}/S^{34}\ (\text{sample})}{S^{32}/S^{34}\ (\text{standard})} \times 1{,}000.$$

RESULTS

The ratio and permil values of the samples analyzed are listed in Table 1. The samples are arranged in groups according to the deposit or mining district from which the samples were collected. Some specimens are listed by the catalogue numbers used in the Economic and Brush Geology collections at Yale University, while others are merely listed numerically. A mineralogic description of each specimen is given and when available the specific geologic location is cited.

All of the ratio results are plotted on Figure 1 to show graphically the spread of the ratios and their relative values where the specimens are separated according to specific deposits on the ordinate, and the isotopic compositions are plotted on the abscissa as ratio values and permil values. The height of the line at a given ratio value is proportional to the number of different samples that have the same ratio value.

The various deposits are separated into four groups on Figure 1. The first three groups are included within the broad category of hydrothermal deposits.

DISCUSSION OF RESULTS

It is believed that through a study of both geology and sulfur isotopic ratios, certain generalizations can be stated about the genesis of the hydrothermal solutions from which these various deposits were formed.

The importance of water in the transport of materials and the formation of mineral deposits was recognized by several investigators during the first half of the nineteenth century. An excellent synopsis of the early development of hydrothermal ideas is given by Bateman (2) where he states that;

> the early nineteenth century writers reverted to the pre-Werner ideas of mineral formation by exhalations from the interior of the earth, recognizing more, however, the significance of water in the formation of veins. Gradually, water of igneous derivation was considered to play the important role. This view received confirmation by the work of Necker (1832), who, believing that the intrusions generated the vein materials, demonstrated the close relationship in various regions, between igneous rocks and mineral deposits.
>
> The connection of the mineral-bearing solutions with magmas was given further emphasis by the French geologists Daubrée, Scheerer, and Elie de Beaumont. . . .
>
> Scheerer in 1847, following Scrope, who concluded that magmatic water played a part in the formation of igneous rocks, stated clearly that water was an important constituent of granitic magmas and that mineral veins were formed by exudations of aqueous solutions from granite intrusions.

TABLE 1

DESCRIPTION AND S^{32}/S^{34} RATIOS OF SPECIMENS

Specimen	Mineralogic and geologic description	S^{32}/S^{34}	‰ S^{34}
	Butte, Montana		
XII–D1–Bu21	Massive, fine-grained, steely chalcocite, Anaconda mine (E–W)	22.21	0.0
XII–D1–Bu52	Predominantly enargite and bornite with pyrite partially replaced by sooty chalcocite. West Colusa mine, 700 L. (E–W)		
	Pyrite	22.20	+ 0.4[5]
	Chalcocite (sooty)	22.21	0.0
XII–D1–Bu59	Coarse grained enargite with fine-grained pyrite. Anaconda vein, 2,200 L. (E–W)		
	Pyrite	22.25	− 1.8
	Enargite	22.25	− 1.8
XII–D1–Bu63	Hydrothermally silicified and sericitized specimen of granitoid rock containing disseminated pyrite cut by a 1 cm wide veinlet of pyrite with some sooty chalcocite. Unknown mine.		
	Pyrite	22.19	+ 0.9
XII–D2–Bu103	Predominantly bornite and chalcopyrite with little pyrite and tetrahedrite. Badger mine, State vein, 2,200 L. (E–W)		
	Bornite	22.21	0.0
XII–D2–Bu104	Galena with little sphalerite. Badger mine, State vein, 1,600 L. (E–W)		
	Galena	22.28	− 3.2
XII–D2–Bu113	Coarse grained galena with very little sphalerite. Elm Orlu mine, 1,300 L. Blue vein (N–W)	22.28	− 3.2
XII–D2–Bu127	Massive coarse grained digenite with chalcocite and chalcopyrite. Leonard mine, 3,000 L. (E–W)		
	Chalcopyrite	22.22	− 0.4[5]
	Chalcocite	22.24	− 0.9
	Digenite	22.24	− 0.9
	Suite of three specimens collected by R. Sales from Leonard mine, 3,500 L., from an ore vein cut by a post ore dike (23).		
XII–D2–Bu128	Copper ore containing blebs of chalcopyrite scattered through bornite located 10′ from dike.		
	Bornite and chalcopyrite	22.19	+ 0.9
	Bornite	22.20	+ 0.4[5]
XII–D2–Bu129	Copper ore of chalcopyrite, pyrite and bornite located 15′ from dike.		
	Chalcopyrite	22.20	+ 0.4[5]
	Bornite	22.20	+ 0.4[5]
	Chalcopyrite and pyrite	22.19	+ 0.9

TABLE 1 (*Continued*)

Specimen	Mineralogic and geologic description	S^{32}/S^{34}	$^0/_{00}$ S^{34}
XII–D2–Bu130	Copper ore of massive pyrite rimmed by chalcocite located 100′ from dike.		
	Chalcocite	22.20	+ 0.4[4]
	Pyrite	22.19	+ 0.9
	La Prieta Mine, Parral, Mexico		
1.	Surface gossan specimen in which nonoxidized galena occurs.		
	Galena	22.43	− 9.9
2.	Banded (cockade) ore specimen consisting of layers of sphalerite and little galena separated by massive bluish-gray quartz. (1,800 L.)		
	Sphalerite	22.32	− 5.0
3.	Sphalerite (Blackjack) ore specimen cross-cut by later quartz. (1,800 L.)	22.33	− 5.4
4.	Coarse grained sphalerite cross-cut by later quartz. Contains specks of chalcocite. (2,075 L.)	22.34	− 5.9
	Bathurst-Newcastle Area, New Brunswick, Canada		
	(Specimens and descriptions from Wm. Tupper)		
1.	Pyrite (possibly introduced) taken from chloritic schist approximately one hundred feet south of the Brunswick Mining and Smelting No. 6 orebody	21.94	+12.2
2.	Massive-fine grained pyrite taken from and believed representative of the Brunswick Mining and Smelting No. 6 orebody	21.91	+13.5
3.	Massive fine grained pyrite taken from and believed representative of the Brunswick Mining and Smelting No. 12 orebody	21.94	+12.2
4.	Pyrite taken from the McMaster pyrite body found four miles north of Caribou deposit	22.04	+ 7.7
5.	Pyrite grains disseminated throughout a quartz-porphry found three miles north of Anaconda's "Caribou" sulfide deposit. The quartz-porphry is a gray colored rock with quartz and/or feldspar phenocrysts in a crystalline to schistose matrix of feldspar, quartz and sericite	22.10	+ 5.0
6.	Pyrite disseminated throughout the same rock type as No. 5. Sample taken one mile east of Anaconda's "Caribou" deposit	22.06	+ 6.8
7.	Pyrite disseminated throughout a green-black slate found approximately 100 feet south of the Brunswick Mining and Smelting No. 12 orebody	22.15	+ 2.7
8.	Pyrite grains disseminated throughout a black slate found one mile north of 44 Mile Brook Lake	22.54	−14.9

TABLE 1 (*Continued*)

Specimen	Mineralogic and geologic description	S^{32}/S^{34}	‰ S^{34}
	Kennecott, Alaska		
XII-D2-Kn84	Massive specimen of coarse to fine-grained chalcocite with very little covellite. Jumbo mine, 1,050 level, 1,050 stope.		
	Chalcocite	22.17	+ 1.8
XII-D2-Kn102	Massive "steely" chalcocite which has partly replaced coarse-grained, milky-white calcite. Bonanza ore-body, 700 L, 718 ore-body.		
	Chalcocite	21.90	+14.0
XII-D2-Kn1128	Polished mineralographic specimen of fine-grained covellite partially replaced by numerous veinlets of chalcocite (up to 0.5 mm in width), both replacing chalcopyrite. Specific location unknown.		
	Chalcocite	22.20	+ 0.4[a]
	Chalcopyrite	22.21	0.0
	Covellite	22.23	− 0.9
XII-D2-Kn64	Approximately 3 cm wide very coarse-grained veinlet of covellite with minor digenite remaining on two sides as enclosing host mineral. The covellite veinlet is cut and replaced by relatively smaller veinlets, some of which are composed of a fine-grained mixture of covellite and chalcocite (digenite?), whereas others consist entirely of digenite. Refer to (11) for photograph.		
	Enclosing digenite host	22.64	−19.4
	Coarse-grained covellite veinlet	21.91	+13.5
	Small veinlet consisting of mixture of digenite and covellite	22.88	−30.2
XII-D2-Kn34	Medium-grained (0.5 mm wide) feathered crystals of covellite in a 2–3 mm wide veinlet that cuts a fine-grained covellite host. Veinlet may have formed by hypogene replacement of covellite host although uniform width and uncurved plane of veinlet suggest possibility of small scale fracture filling.		
	Veinlet covellite	21.85	+16.2
	Host covellite	22.37	− 7.2
	Bristol, Conn.		
XII-D6-Br284	Large ore specimen that contains chalcopyrite, pyrite, and barite associated with quartz. Pyrite occurs in fine-grained masses and as cubes although a very few octahedral crystals are evident. Radiating and essentially parallel plates of barite crystals appear to be contemporaneous with the pyrite but earlier than the quartz.		
	Chalcopyrite	22.34	− 5.9
	Pyrite massive	22.42	− 9.5
	Pyrite crystal (small)	22.19	+ 0.9
	Pyrite crystal (large)	23.04	−37.7
	Barite	—	—

TABLE 1 (*Continued*)

Specimen						Mineralogic and geologic description	S^{32}/S^{34}	$^0/_{00}$ S^{34}
XII–D6–Br990						Aggregate of orthorhombic chalcocite crystals varying in size from less than 1 mm to over 20 mm in diameter.		
						Chalcocite	23.10	−40.1
Brush 816						Veinlets of bornite and minor chalcopyrite cutting and replacing calcite. Chalcopyrite appears to have replaced bornite.		
						Bornite	22.27	− 2.7
						Chalcopyrite	22.28	− 3.2
Brush 1099						Typical aggregate of orthorhombic crystals of chalcocite for which Bristol is well known.		
						Chalcocite	22.91	−31.5
						Buchans mine, Nfld, Canada		
						(Specimens and descriptions from B. H. Relly)		
						Mill concentrates which were concentrated further in the laboratory by flotation. All specimens are from the only ore body which is now being mined at Buchans (1957).		
	Cu	Pb	An	Fe	$BaSO_4$			
1.	30.3	2.12	3.3	27.1	.23	Chalcopyrite	22.12	+ 4.1
2.	0.52	78.0	3.1	1.3	tr	Galena	22.13	+ 3.6
3.	0.70	2.1	62.7	1.0	0.10	Sphalerite	22.08	+ 5.9
4.	0.26	0.7	0.3	45.0	0.1	Pyrite	22.07	+ 6.3
6.						Barite from the barite-rich band of ore in the hanging wall of ore body R1. The sample was leached with HCl and HNO_3 to remove sulfides and carbonates.		
						Barite	21.68	+23.9
7.						Vug barite that occurs as milky or clear crystals lining the walls of fractures in the barite rich parts of the North ore body. The sample contained no visible sulfides.		
						Barite	21.71	+22.5
8.						Mixed sulfides (chiefly pyrite, chalcopyrite, galena and sphalerite). From the "footwall" orebodies, not at present being mined. This ore differs in several respects from the other ore. The gangue is quartz and calcite, not barite. The texture is much coarser; the ratio of Cu to Pb and Zn is relatively higher. This particular sample, part of a drill core, was crushed and sized (20–80 mesh) then concentrated by flotation to remove the gangue. It contains probably less than 0.5% barite or calcite.		
						Mixed sulfides	22.09	+ 5.4
9.						Pulverized half-inch cubes of pyrite from the chloritic foot wall of North Orebody.		
						Pyrite	22.06	+ 6.8

TABLE 1 (*Continued*)

Specimen	Mineralogic and geologic description	S^{32}/S^{34}	‰ S^{34}
10.	Unusually coarse sphalerite crystals from the diabase dike in F1 orebody. This is the only place such sphalerite has been found, the relationship to the dike is not understood, but most evidence indicates the ore is later. The other minerals do not show comparable changes near the dike.		
	Sphalerite	22.08	+ 5.9
	Mercur, Utah		
	(Specimen collected by R. Rubright)		
1.	Gypsum specimen (selenite variety) which entirely encloses euhedral to subhedral crystals of pyrite. There is no evidence of oxidation of the sulfide and it is believed that the two minerals formed penecontemporaneously.		
	Pyrite	22.20	+ 0.4[5]
	Gypsum	21.87	+15.3
	Duluth Gabbro, Minnesota		
	(Specimens and descriptions from Paul Bailly)		
1.	Massive chalcopyrite and cobalt-bearing arsenopyrite in a shear zone in Logan diabase sill. Collected from Blankenberg prospect on the South arm of Loon Lake north of the Gunflint Trail, T65N, R3W, Section 34, Minn.		
	Chalcopyrite	22.15	+ 2.7
2.	Chalcopyrite in altered gabbro in the basal zone of Duluth Gabbro lopolith. Collected in road cut on north side of the Gunflint Trail, T65N, R3W, Section 33, Minn.		
	Chalcopyrite	22.13	+ 3.6
3.	Same location description and possible origin as sample (2).		
	Chalcopyrite	22.13	+ 3.6
4.	Chalcopyrite in coarse-grained gabbro from basal zone of Duluth Gabbro lopolith. Collected 1,000 feet north of intersection of Gunflint Trail and South Lake foot trail in T64N, R2W, Section 1, Minn.		
	Chalcopyrite	22.28	− 3.2
5.	Blebs of chalcopyrite and pyrrhotite in olivine gabbro at base of Duluth Gabbro lopolith. Collected in road cut along Gunflint Trail, T65N, R3W, Section 30, Minn.		
	Chalcopyrite and pyrrhotite	21.89	+14.4
	Mellen Gabbro, Wisconsin		
6.	Pyrrhotite and chalcopyrite in altered pyroxenite. Central zone of Mellen Gabbro. Collected at Burabee prospect in T45N, R3W, Section 33, Wisconsin.	22.13	+ 3.6
7.	Pyrrhotite in quartzite, from the basal zone of the Mellen Gabbro, that is believed to be an inclusion of Tyler Slate formation. Collected at Penokee Veneer Mill "show" in T44N, R2W, Section 6, Wisconsin	21.88	+14.9

Evidently, Elie de Beaumont (19, p. 82) was not only one of the first to suggest the possibility of aqueous deposition, but he furthermore testified to the much greater importance of volcanic (magmatic) water over infiltrated surface (meteoric) water as the source of mineralizing solutions. Nevertheless, the opposite view, that magmatic water is of little importance, seemed to prevail until the turn of the century, supported primarily by the influential writings of Daubrée (who in 1887 had become a firm supporter of a vadose source of water for ore solutions), Hunt, Phillips, and S. F. Emmons. Shortly after 1900, however, with the swing of the pendulum, the views changed to such an extent that if no intrusive body was evident near a hydrothermal deposit a hidden intrusive must exist, as the expression goes, "at depth."

The meaning of *hydrothermal* was, according to Johannsen (15), first used by Bunsen (4) in 1847 in referring to those minerals produced by the agency of heated water. The term has also been used in referring to the heated solutions themselves and to the type of alteration caused by these heated solutions. Fay (7), however, merely defines the term as "pertaining to hot water." There is no implication of an igneous source attached to this definition. Niggli (20a, p. 515) states that the term "hydrothermal solution" used without the adjective "magmatic" does not imply that the solution was separated from a magma. Many geologists agree with this view. Many would also agree, however, that a magma is the major source of hydrothermal solutions; in fact so many, that the AGI Glossary (10) states that hydrothermal is a term applied to heated or hot *magmatic* (italics mine) emanations. . . ." Be that as it may, few deny that hydrothermal solutions composed essentially of heated meteoric water are effective in transporting and depositing various minerals at the orifice of hot springs. It does seem desirable, therefore, to retain this broad "hot water" definition of hydrothermal solutions but to be more specific in stipulating the surmised source of these solutions by the use of further suitable modifying adjectives. For example, the terminology used in this paper consists of 1) magmatic hydrothermal, 2) metamorphic hydrothermal, and 3) ground water hydrothermal deposits. The latter is meant to include both heated meteoric and connate water solutions.

Magmatic Hydrothermal Deposits.—Many hydrothermal mineral deposits exhibit remarkably constant isotopic ratio values for all sulfur-bearing minerals within the deposit. Other hydrothermal deposits exhibit a spread of ratio values over a relatively broad range. The first type is apparently more common. The latter, however, for the most part includes those deposits of a more controversial origin.

Several deposits for which S^{32}/S^{34} ratios of relatively narrow spread have been determined are listed on Figure 1 under magmatic hydrothermal deposits.

The small suite of samples from Butte, Montana, is large enough to indicate that sulfide specimens from this district vary in S^{32}/S^{34} values over a small range of less than 5 permil. Even a specimen (Bu 113) from the Blue vein system has a ratio value identical with some of the ratios obtained from the more common specimens from the Anaconda system. As the paragenetic

relationships of these two systems is sequential (or penecontemporaneous if rotational stresses could have formed the Butte fracture systems), this may be an indication of a lack of isotopic fractionation of the sulfur in the ore-bearing solutions. It is, furthermore, an additional hint of a common source of (at least) sulfur in the ore solutions. A single ore solution reservoir has generally been considered to be the most logical common source, as was first pointed out by Sales (22) for the mineralization occurring in the three different vein systems. His evidence is essentially the close association of the ore veins with the late forming quartz porphyry dikes that were derived from the intrusive, and the repetition of the same ore-bearing minerals having similar paragenetic relationships within the three systems. The relatively consistent values of the isotopic ratios support Sales supposition of a common well-homogenized ore solution as the source of mineralization.

Incidentally, samples Bu 128, 129 and 130 were collected a distance of 10, 15 and 100 feet, respectively, from one of the post-ore dikes described by Sales and Meyer (23). Although the heat from the dike provided the energy for diffusion and the formation of new sulfide minerals near the dike, there is no evidence of isotopic fractionation of the sulfur. There is, of course, little expectation of diffusion of the large sulfur anions during the more rapid diffusion and mixing of the iron and copper cations even though there was loss of sulfur during the reaction between pyrite and chalcocite to form chalcopyrite and bornite.

The search for evidence of isotopic fractionation of sulfur from sulfides during hypogene mineralization has not been too successful although the hypogene sulfates that in some cases accompany primary sulfides do commonly exhibit a great enrichment in the heavier isotope. Appreciable isotopic fractionation during primary sulfide mineralization in one magmatic hydrothermal deposit is, at least, rare if not non-existent. Some evidence might be cited, however, such as the example offered by the four specimens collected over a vertical distance in excess of 2,000 feet from the Prieta vein, La Prieta mine, Chihuahua, Mexico. As the mineralogy of the specimens is different (Table 1) I would certainly not cite this example in support of fractionation. Furthermore, these few (four) samples do not show a consistent variation with depth although, admittedly, the paragenetic relationships of these samples are unknown. Certainly one need not stress the fact that a near surface specimen in a vein of a few score feet in width is not at all necessarily of an earlier age than some sulfides at much greater depth nor necessarily of a later age either. In another search for hypogene isotopic fractionation of sulfides, Sakai (21) has reported the sulfur ratios of 13 sulfides collected from several of the epithermal veins of the Yoichi mine, Hokkaido, Japan. There is no systematic variation of their ratios with respect to either their vertical position or the ore vein from which the specimens were ecollected.

It is possible that evidence of isotopic fractionation of sulfur in sulfides during primary mineralization might be obtained only by a statistical study of numerous sulfides of the same species of well-established sequential paragenesis. In other words, if the statistical averages of the ratios of the speci-

mens of different mineralizing stages exhibit ratio differences, possibly differences not greater than several permil, isotopic fractionation may be indicated.

One should not confuse the appreciable variations in S^{32}/S^{34} ratios noted and previously reported (11) for some juxtaposed sulfide minerals as evidence of isotopic fractionation during hypogene mineralization. Instead, these appreciable variations seem to be more logically the result of derivation of sulfur from different sources, sulfur sources varying of course in isotopic composition.

The ratios reported by Kulp, Ault, and Feely (18) for Santa Rita were obtained not from the Chino mine (open pit) but from three small mines, two in the north and one in the southern portion, of the Santa Rita mining district. One might be surprised, therefore, with the uniform grouping of the ratios over this area, but if the ore solutions were derived from the same intrusive, in which the solutions became well homogenized, the uniformity of the ratios is just what should be expected.[1]

Sulfides from Sudbury provide a good example of the reliability and precision of sulfur isotopic studies performed at different laboratories by different personnel (11, 18, 20). The samples analyzed only vary in ratio values between 22.08 to 22.18. Once again, the mineralization is intimately related to the igneous body from which it is believed the ore solutions were derived whether, for this district, the process be magmatic hydrothermal or magmatic segregation.

An isotopic study of sulfides from the Cerro de Pasco deposit has been completed and will be presented later in detail by Jensen and Amstutz (14). As the mineralization is closely associated with the stock from which it is believed the solutions were derived, the samples all show very similar ratio values, with the exception of two specimens that were formed last in the paragenetic sequence. The two minerals are gratonite and reveredoite. One wonders, because of its significantly different isotopic composition (23.03), if the enigmatic reveredoite, which is an arseno-sulfide glass mineral, is actually related to the hypogene period of mineralization at all.

The discoveries of numerous sulfide deposits in the Bathurst-New Castle, New Brunswick area have resulted in at least two hypotheses for the origin of the mineralizing fluids. Mobilization of volatile components and sulfides (which are dispersed in the surrounding sediments and volcanics) is one suggestion; the other is magmatic hydrothermal solutions derived from the granite exposed in the area.

A dissertation study by E. Dechow (5), a portion of which pertains to the primary and supergene sulfides of the Heath Steele deposits, indicates a remarkably uniform ratio of samples as shown by the hatchured lines of Figure 1. The preliminary cursory results of a second more regional study of the Bathurst area undertaken by William Tupper (27) provides initial ratios for eight samples described in Table 1 and shown in Figure 1. Samples 1 to

[1] Even more convincing evidence of the homogenous-ore-solution-source idea is now being obtained from an isotopic study of an extensive collection of sulfide minerals from the Lark, U. S., (vein and replacement deposits), and the Utah (open pit disseminated deposit) mines of the Bingham district for which the single mineralizing source is believed to be, of course, the Bingham stock.

4 were collected within or close-by ore bodies of the area. Samples 5 and 6 were collected from quartz porphyry, and samples 7 and 8 were obtained from the metamorphosed sediments of the district. It is interesting to note that these last two samples have ratio values, 22.15 and especially 22.54, that are significantly different from the ratios of the ore body samples. Possibly, therefore, rather well homogenized magmatic solutions may be a more logical source for the ore solutions than mobilized sedimentary sulfides, sulfides that commonly vary much in ratio values. No samples from the volcanics have as yet been studied; Dechow and Tupper are, however, including samples from this source in their studies.

Metamorphic Hydrothermal Deposits.—Several investigators (9, 24) have suggested that the process of regeneration or mobilization of the more volatile constituents from rocks undergoing, for example, regional metamorphism may be capable of producing hydrothermal solutions. The composition of the solutions may differ only little if at all from what is presumed to be the composition of magmatic hydrothermal solutions.[2] There does, however, seem to be a difference in the degree of mixing experienced by these two types of hydrothermal solutions. Magmatic hydrothermal solutions presumably become more and more concentrated and thereby homogenized in the latest crystallizing phase of an intrusive body, whereas metamorphic hydrothermal solutions might be derived from heterogeneous sources and may never have a chance of extensive intermingling before any locale of deposition or mineralization is reached. In this latter case, the mobilization of sulfur, whether it is in the form of hydrogen sulfide or even as mineral sulfides (which is less likely), might result in a concentration of the transported material through structural control of the ore solutions or through preferential replacement of a congenial host rock. In any case, owing to a lack of homogenization of the hydrothermal solutions, one might expect a variation in at least the sulfur isotopes in the deposit as they were most likely derived from heterogeneous sulfur sources such as syngenetic sedimentary sulfides that vary greatly, even juxtaposed samples, in S^{32}/S^{34} ratios.

It may be that Kennecott, Alaska, had an origin similar but not identical to this generalized hypothesis. The spread in δ values, almost 50 permil, is greater than that known for any other deposit, with the possible exception of the enigmatic Franklin Furnace deposit. At Kennecott, furthermore, there is no igneous stock associated with the ore bodies except for a monzonite porphyry "which is $1\frac{1}{2}$ miles distant and apparently not directly related to the deposit" (19, p. 420). The large bodies of rich chalcocite ore have formed by replacement of the lower dolomitic beds of the Chitistone limestone which overlies 5,000 feet of the Nikolai greenstones (3). These metamor-

[2] The initial cursory results of a dissertation study by J. Allen, in the Laboratory of Economic Geology at Yale University, on the elemental and isotopic composition of fluid inclusions indicate appreciable variations in the relative amounts of water and carbon dioxide (and other constituents) contained in fluid inclusions in quartz specimens that formed in a pegmatitic vein within only a few centimeters of each other. This is, therefore, a strong indication of an appreciable change in the composition of some hydrothermal solutions presumably within only a short interval of time.

phosed basalt flows contain "specks of native copper, chalcocite, bornite, and chalcopyrite. Copper sulfides also occur in slips, brecciated zones, and faults. Even the apparently fresh greenstone contains copper" (19, p. 418).

Iron is so rare in the ore bodies that no pyrite is found and bornite is not common. As the vapor pressure of ferrous sulfide is about 10^6 atmospheres lower than that for copper sulfide at 600° C (17) is it possible that mobilization is not only a partial explanation for the lack of iron sulfides at Kennecott but also a possible hypothesis for the origin of this deposit?

Edwards (6), incidentally has cited evidence of significant volatility of sulfides, especially copper sulfides, and suggests, furthermore the possibility of increased volatility of metal sulfides when in a sulfur vapor or hydrogen sulfide atmosphere.

In reference to Kennecott, however, during the Laramide Revolution, hydrothermal solutions could have been created throughout the basalt flows in this portion of the Cordilleran geosyncline. These solutions may have removed part of the relatively high content of copper in the basalt flows undergoing metamorphism and transported it to the overlying Triassic dolomites where the temperature was indeed low, possible averaging about 100° C as both digenite and orthorhombic chalcocite occur within the deposit. This process, using meteoric water as the solvent, was suggested as a possibility by Bateman and McLaughlin (3) although they favored the presence of a magma as the temperature source. Lindgren (19, p. 420), however, has concluded that "the magmatic origin of the solutions cannot be regarded as proved conclusively." The existence of S^{32}/S^{34} variations in an extensive series of basalt flows might first be ascertained before this suggested origin is considered more seriously.

Incidentally because of the appreciable variations in the S^{32}/S^{34} ratios of the three mineral phases of specimen Kn 64, a copper isotopic analysis was made of these three phases by the U. S. Geological Survey in order to determine the Cu^{63}/Cu^{65} ratio. The slight permil deviations from a standard of the digenite, covellite vein, and digenite-covellite veinlet were -0.13, $+0.47$, and -0.01 respectively (25). As these values are within the precision of the measurements, no measurable variation of the copper isotopes exists.

It is merely a suggestion that the Joplin district be classified in this paper as a metamorphic hydrothermal deposit essentially because it also exhibits a spread in the sulfur isotopic ratio as determined by Kulp et al. (18) but also because of the geology of the district. Little, of course, can be said about the genesis of this district without reiterating suggestions that have already been presented to explain the origin of the Mississippi Valley-Tri State districts. The process, however, of mobilizing solutions, preferably from the underlying Precambrian crystalline rocks with little resulting disturbance to the overlying Paleozoic strata, might be adequate to transport sufficient minerals upward to the favorable structural and stratigraphic traps in the Paleozoic strata.

Ground Water Hydrothermal Deposits.—The significance of the ratio values of the fairly large suite of sulfide samples from sandstone-type uranium

deposits on the origin of these deposits has been presented elsewhere (12, 13). To be redundant, however, based upon the evidence of the extremely high ratio values and the moderate spread in ratio values of even juxtaposed samples, I have suggested that hydrogen sulfide gas derived from anerobic bacteria may be not only the source of the sulfur in these deposits but also the agent that provided the reducing environment for the reduction of soluble UO_2^{++} ions to relatively insoluble UO_2, especially in those locales absent of organic matter.

Although no attempt is made in this paper to repeat the evidence given in the previous paper (13) in support of this hypothesis, reference to certain factors should be made. It does seem that the typical isotopic ratio values associated with sedimentary sulfides are commonly (1) enrichment in the lighter isotope and (2) of even greater significance, almost invariably, difference in ratio values of even juxtaposed sulfide samples. It is believed that the reason for these two features is that many sedimentary sulfides form by hydrogen sulfide of organic origin reacting with soluble sulfates or chlorides to precipitate relatively insoluble sulfides. The hydrogen sulfide of organic origin is liberated by anerobic bacteria during their process of reduction of sulfates to hydrogen sulfide. As this process is accompanied by isotopic fractionation, according to the reaction given below, the hydrogen sulfide

$$H_2S^{34} + S^{32}O_4^{=} \rightleftarrows H_2S^{32} + S^{34}O_4^{=}$$

is enriched in the lighter isotope. The enrichment is as great as 7.4 percent at 25° C under equilibrium conditions, but as equilibrium is rarely approached the actual enrichment in nature is generally of the order of 1.5 percent or less. The isotopic fractionation varies significantly and erratically with time, in fact, Feely and Kulp (8) have noted a change of almost 20 permil during a period of less than 3 days in laboratory culture experiments. It is realized, therefore, that a sedimentary sulfide will generally contain sulfur that is enriched in S^{32} and the enrichment will vary not only from that of a nearby sulfide but possibly even within the different growth zones of a single large crystal.

As recent studies (26) by a group under the direction of Prof. H. Thode at McMaster University have indicated remarkably uniform and low ratio values of hydrogen sulfide from crude oil in one pool, it should be mentioned that the very high ratios of the sulfides associated with sandstone-type uranium deposits might be better explained by differences in the bacterial food supply; i.e., crude oil in contrast to only slightly decayed woody material as the energy source. Feely (8) has reported that isotopic fractionation, during reduction of sulfate to hydrogen sulfide by anerobic bacteria, is significantly greater when only a limited or meager food supply is available. Does an abundance of crude oil provide a better food supply for anerobic bacteria, therefore, than woody undecayed material of sandstone-type uranium deposits? One possible source to this answer, other than laboratory experiments, might be provided from an exhaustive study of S^{32}/S^{34} ratios of sulfides formed in peat and the various ranks of coal.

Two other deposits are included within the ground water hydrothermal category. It is my belief that both are "Red Beds" copper deposits.

The Bristol deposit, which has long been inaccessible, is well known for the large orthorhombic chalcocite crystals that occur there. It is not only these crystals but also large pyrite crystals that exhibit the high ratios. Although supergene processes have been postulated (28) for the orthorhombic chalcocite crystals, Bateman (2, p. 270) has shown that this process seems quite unlikely as supergene chalcocite forms almost entirely by replacement of primary hypogene sulfides, not by reduction and precipitation in space from the descending sulfate solutions.

These very light ratios, which also exhibit a spread in values, are suggestive once again of sulfur derived from hydrogen sulfide of anerobic origin. The Bristol deposit is localized along a fault zone that separates crystalline rocks of the Western Upland of Connecticut from the present western edge of Triassic arkose (1). As much of the ore occurs in light gray colored arkosic beds, sediments which it is believed contained organic debris, it does seem possible that anerobic bacteria existing in this organic material could have reduced sulfates, contained in ground water, to hydrogen sulfide that reacted with copper sulfate solutions in the locale of the Bristol deposit. The original source of the copper could have been an already existing deposit undergoing oxidation, or possibly copper leached from nearby rocks having a higher trace amount of copper. Possibly the former source may be preferred as the result of studies on the few samples analyzed so far suggest, although this is far from certain, that the veinlet copper sulfides do exhibit lower and less variable ratios.

The Happy Jack deposit exhibits ratios that are quite typical for sulfides in sandstone-type uranium deposits. It would seem somewhat unusual to call upon an *ad hoc* magmatic hydrothermal source of mineralizing fluids to explain this deposit when the precipitation of copper sulfides may be brought about by the same hydrogen sulfide that is suggested for the formation of the sulfides and uranium deposits of other deposits of the area. The problem, if any, is to provide a source of copper that may be transported within the ground water hydrothermal solutions; a possible source may have been the leaching of copper from nearby rocks in which the concentration was somewhat higher than usual.

It is necessary that an explanation be given for the terminology used for this category. As heated meteoric ground water solutions are certainly capable of being classified as hydrothermal and connate water has been suggested as the essential source of solutions for the uranium deposits of the Colorado Plateau, it is suggested that as ground water hydrothermal would include both sources no restriction of the use of this classification arises when the exact source of the ground water be either meteoric or connate. The reader is undoubtedly aware that lateral secretion hydrothermal might also be acceptable as the title of this category but it has been avoided primarily because of the notoriety and partly unwarranted disapproval that this termed process has met with in the past which might prevent a critical appraisal of

the process here suggested. Incidentally, it is interesting to note that Lindgren (19) included within his classification a somewhat similar process but evidently favored describing it not tersely with few words but instead as "Deposits Formed by Concentration of Substances Contained in the Surrounding Rocks, by Means of Circulating Waters."

Miscellaneous Samples.—A few additional sulfur isotopic ratios are included in this paper primarily because of the interesting questions that might be raised pertaining to their significance.

The Buchans deposit, Newfoundland, is thought to be a typical hydrothermal mesothermal replacement deposit. The few sulfides from the deposit that have been isotopically analyzed exhibit a narrow spread in ratio values, but of more immediate concern are the two significantly lower ratios obtained for two barite samples from the deposit, which are considered to be of hypogene origin and contemporaneous with the sulfide mineralization. Barite is not an uncommon hypogene mineral although the derivation of sulfate minerals from reducing primary mineralizing fluids is surprising to many. If one assumes that hypogene sulfides derive their sulfur from hydrogen sulfide in an ore fluid in which oxidation is also providing sulfate ions, the possibility of a method of geothermometry is provided. The basis of the method is the following isotopic equilibrium reaction:

$$S^{32}O_4^{=} + H_2S^{34} \rightleftarrows S^{34}O_4^{=} + H_2S^{32}.$$

The variation of the isotopic equilibrium constant with temperature is shown in Figure 2. Under equilibrium conditions, the isotopic ratios of sulfates and sulfides gradually approach a common value at higher temperatures, i.e., the partition function ratios approach unity. Using the ratios of 22.08 for sulfides and 21.70 for sulfates determined for the Buchans samples the enrichment factor is $22.08/21.70 = 1.018$. Referring to Figure 2, a temperature of about 350° C is indicated for the deposit. This is, of course, rather high and it seems most likely at best, therefore, that isotopic equilibrium conditions were not obtained, although this method might be considered to be an indication of a maximum temperature.

The Mercur sample, consisting of several pyrite crystals, is more unusual as the pyrite is enclosed within gypsum (selenite variety) that formed evidently contemporaneously with the sulfide. The temperature indicated by the isotopic exchange reaction of $H_2S - SO_4^{=}$ is about 540° C, which is excessively high for this deposit.

Sakai (21) has determined the sulfur ratios of sulfides and barite of hypogene origin from several mines in Japan. These deposits are all epithermal replacement bodies of mixed sulfides that occur in andesites, associated tuffs, and some Tertiary sediments. The temperatures obtained based upon these ratios range between about 340° C to over 700° C. Significantly, however, Sakai reports temperatures between 120° C to 360° C based not on the $H_2S - SO_4^{=}$ exchange reaction but upon the $H_2S - SO_2^{=}$ exchange reaction. This is used because this "reaction is the most probable process

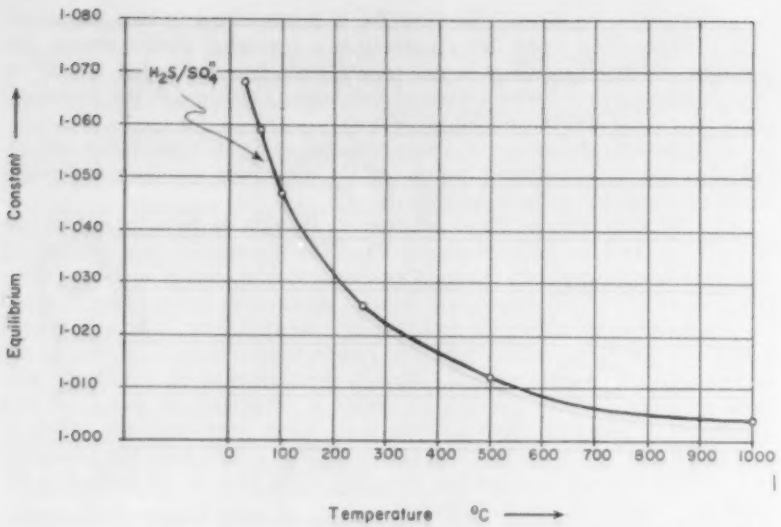

FIG. 2. Variation in fractionation factor versus temperature for $H_2S - SO_4^=$ isotopic equilibrium reaction (after Sakai).

to interpret the isotopic ratio in hydrothermal deposits and sulfur compounds of exhalative origin," says Sakai (21).

Nevertheless, with the above evidence of non-equilibrium of the $H_2S - SO_4^=$ isotopic reaction, even though these lower temperatures are more reasonable, one should have serious doubts about the reliability of this geothermometry method. On the other hand, more isotopic studies of primary sulfates and sulfides of contemporaneous or penecontemporaneous paragenesis may further support the supposition that sulfate ions in the supposedly reducing environment of hydrothermal solutions are actually formed by oxidation of sulfur as is suggested by the presently available isotopic results. Hydrogen sulfide, for example, may be oxidized to sulfate ions in hydrothermal solutions even though the partial pressure of oxygen may be relatively low—the relative abundance of primary sulfates might, in fact, be an indication of the partial pressure of oxygen. The resulting minor oxidation of sulfur that does take place results in the enrichment of heavy sulfur in the sulfate ions according to the $H_2S - SO_4^=$ isotopic reaction, although as indicated not under equilibrium conditions. Most of the resulting sulfate finally forms as barium, calcium or strontium sulfates. Even though equilibrium conditions are not attained fractionation does take place as is evident from the Buchan's suite, the Mercur pair of minerals, and Sakai's study (21).

This whole interesting question about the origin of hypogene sulfates might have considerable information shed upon it by an increase in this type of iso-

topic studies. It is possible that hypogene sulfates are derived merely by assimilation of original sulfates during the formation of a magma or by later stoping. Another possibility might be oxidation of sulfur dioxide (which certainly is abundant in high temperature fumarolic gases), although much more of this gas would be reduced at lower temperatures to hydrogen sulfide. Both sulfur and oxygen isotopic studies should certainly be of aid in strengthening or weakening these suppositions.

It should be noted that no evidence has been obtained as yet to indicate that supergene oxidation results in any undoubted measurable isotopic fractionation which, in contrast, is certainly apparent for hypogene sulfides and sulfates. The distinction, furthermore, between isotopic fractionation as the result of equilibrium reactions on the one hand, and fractionation of sulfides alone on the other hand, should be emphasized. The latter case is not, of course, the result of oxidation or reduction and valence changes of sulfur, but is instead fractionation by differential mobilization, e.g. diffusion with S^{32} ions or compounds being more mobile than similar S^{34} ions or compounds; the relative mobilities are determinable, at least for gases, by Graham's Law.

In summary, therefore, oxidation of sulfur-bearing minerals may result in the formation of sulfate minerals under both hypogene and supergene conditions; isotopic fractionation occurs in the former case but has not been detected in the latter case. Reduction of sulfates, on the other hand, is apparently accomplished in nature only by anerobic bacteria and apparently does not take place by inorganic reactions.

As if not enough problems have already arisen or been suggested, the sulfur ratios of several sulfide samples from the Duluth Gabbro and the Mellen Gabbro are reported. One might expect at least the former to exhibit somewhat of a more narrow spread possible in more agreement with the close grouping shown by the Sudbury samples. Samples 2 and 5 were both obtained from the base of the lopolith and from the same rock type, although located several miles apart, and their ratios are quite different. Evidently, as some have suggested, there may have been some differences in the processes of sulfide concentration that have taken place in the Sudbury and Duluth lopoliths.

CONCLUSION

It has been said that an indication of progress is obtained when a research project enables one to ask more new questions than the project has provided answers for. It is hoped that the students of ore genesis might be further stimulated by some of these results to the extent that not only many more questions might be asked, but that a few answers might also be obtained.

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GEOLOGY AND URANIUM-VANADIUM DEPOSITS OF THE SLICK ROCK DISTRICT, SAN MIGUEL AND DOLORES COUNTIES, COLORADO[1]

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ABSTRACT

Sedimentary rocks known in the Slick Rock district in southwestern Colorado range in age from Devonian (?) to Cretaceous, and aggregate about 13,000 feet in maximum thickness. Important uranium-vanadium production has come from deposits in the Salt Wash member of the Morrison formation of Late Jurassic age.

The sedimentary rocks are gently folded in the Dolores and Glade anticlines and the Disappointment syncline, and are cut by the Dolores fault zone in the north part of the district and by the Glade fault zone in the south part of the district. Principal fracture sets are oriented approximately parallel to the major faults.

Detrital hematite, magnetite, and ilmenite in rocks of the Morrison formation not affected by epigenetic alteration contain appreciable amounts of several of the elements found in the ore deposits. Epigenetic alteration processes have bleached large volumes of rock and largely destroyed these minerals. Such alteration is spatially associated with the Dolores fault zone.

Most of the known ore deposits are in the north part of the Slick Rock district in a belt called the Dolores ore zone. The zone lies along the Dolores fault zone but is wider than the fault zone. All known deposits are associated with abundant carbonaceous plant material.

Uranium-vanadium deposits in the district are chiefly tabular to lenticular and are roughly parallel to the sedimentary bedding. Some ore bodies, however, are narrow, elongate, and curve sharply across bedding;

[1] Publication authorized by the Director, U. S. Geological Survey.

these bodies have been called "rolls" by the miners. Mineral zoning is evident in some roll bodies; carbonates, goethite (altered from pyrite), selenides, and sulfides are commonly found in concentric layers at the concave edge of rolls. This zoning, and the relationship of roll ore bodies to sedimentary structures and lithology, suggest that ore was deposited at an interface between two solutions, possibly cool connate water and a warmer ore solution.

On a district scale, copper and lead are distinctly most abundant in the ore deposits within and immediately adjacent to the Dolores fault zone, and less abundant in deposits toward the edge of the zone.

Uranium-vanadium deposits in the district occur only in sandstone that is considered to be epigenetically altered, and the most extensive epigenetic changes have occurred close to ore bodies.

It is concluded that ground water, heated and set into circulation near the end of Cretaceous time by igneous intrusions in the La Sal and other centers on the Colorado Plateau, picked up elements from sedimentary rocks where they had been faulted and fractured, and deposited the elements at solution interfaces where accumulations of carbonaceous material provided favorable chemical conditions for precipitation.

INTRODUCTION

THE Slick Rock district occupies about 570 square miles in the western parts of San Miguel and Dolores Counties, Colo. (Fig. 1). The U. S. Geological Survey began a geologic program in the district in 1953, with the objectives of evaluating previous diamond drilling in the district, extending exploratory drilling to areas where possible uranium deposits are deeply buried, synthesizing previous geologic studies pertaining to the district, and undertaking additional studies. The purpose was to present a comprehensive picture of the geology and ore deposits of the Slick Rock district, and to discern the origin and genesis of the deposits.

STRATIGRAPHY

Sedimentary rocks cropping out in the Slick Rock district range in age from Permian to Cretaceous. Older sedimentary rocks that underlie these are known to rest on igneous and metamorphic rocks of a probable Precambrian basement. Maximum thickness of exposed sedimentary rocks in the district is about 4,700 feet and the total section of sedimentary rocks underlying the district is about 13,000 feet. Only one igneous intrusive rock is known in the district, but several igneous sills and dikes probably related to the San Juan volcanic province lie not far to the east.

Data on consolidated sedimentary rocks in the district are summarized in Table 1.

STRUCTURE

The Slick Rock district lies in the Paradox Basin at the south edge of the salt anticline region. Major folds in the district trend about N 55° W and parallel the collapsed Gypsum Valley anticline (Fig. 2). The Dolores anticline is about 9 miles southwest of the Gypsum Valley anticline; the Disappointment syncline lies between the two anticlines. In the southeast

FIG. 1. Map showing location of the Slick Rock district, San Miguel and Dolores Counties, Colo.

part of the district the Glade anticline branches eastward from the Dolores anticline.

A zone of faults bounding the southwest edge of the collapsed core of the Gypsum Valley anticline lies along the southwest limb of the anticline. The Dolores fault zone is about 2 miles northeast of and parallel to the axis of the Dolores anticline. Individual faults in the zone strike N 60° to 85° W and form a series of small en echelon grabens. The zone extends northwestward toward the Lisbon Valley anticline in Utah. A few faults normal to the Dolores fault zone in the northwest part of the district form a conjugate set. The south part of the district is cut by the Glade fault zone, which trends about N 80° E and extends westward into the Verdure graben in Utah. Individual faults in the zone strike about N 60° to 70° W; depression of a

TABLE 1

GENERALIZED STRATIGRAPHIC SECTION OF ROCKS IN THE SLICK ROCK DISTRICT, SAN MIGUEL AND DOLORES COUNTIES, COLO.

Age	Formation and member	Thickness in feet	Character	Distribution and remarks
Quaternary	Soil, alluvium, and talus		Thin residual soils, talus deposits, recent alluvium	Cover small areas throughout district
	Loess			Thin blanket covers high plains in south part of district
	Terrace gravel		Well-rounded cobbles and pebbles derived from volcanic rocks of San Juan Mountains	At least five levels occur along Dolores River and its tributaries
	Landslide, mudflow, and alluvial fan deposits			Developed along canyon walls
	Glacial till		Poorly sorted fine-grained to boulder size, angular to rounded volcanic matrials	Found on Glade Mountain in southeast part of district
	UNCONFORMITY			
Late Cretaceous	Mancos shale	2,300	Dark-gray calcareous mudstone and minor limestone, bentonitic claystone, and sandstone. Contains abundant invertebrate fossils	No complete section known in district. Lower 855 feet separable into six fossil zones. From base upward: Early Greenhorn, Late Greenhorn, Earlier Carlile, Later Carlile, Earlier Niobrara, and Later Niobrara
	Dakota sandstone	120–180	Fine-grained quartzose sandstone, carbonaceous shale, coal, and locally conglomeratic sandstone	Forms present surface of much of district, forms cliffs where exposed in canyons. In Disappointment Basin lower contact conformable, sharp. Thickest in Disappointment syncline

TABLE 1—*Continued*

Age	Formation and member	Thickness in feet	Character	Distribution and remarks
	UNCONFORMITY			
Early Cretaceous	Burro Canyon formation	80–300	Fine-grained to conglomeratic light-gray to light-brown quartzose sandstone, greenish-gray shale and siltstone, and greenish-gray to gray limestone and chert	Sandstone caps benches, forms cliffs; shale and siltstone with minor sandstone, limestone, chert, forms smooth ledgy slopes. Contact with underlying Brushy Basin member of Morrison transitional, in places intertonguing or disconformable. Thickest in Disappointment syncline
Late Jurassic	Morrison formation: Brushy Basin member	300–720	Predominantly reddish-brown bentonitic mudstone of volcanic origin	Crops out as smooth slope with low ledges. Thickest in Disappointment syncline, thinnest on Dolores anticline
	Morrison formation: Salt Wash member	275–450	Lenticular quartzose sandstone, interbedded reddish-brown mudstone. Sandstone lenses in top part dominantly light-brown or light-gray, contain abundant carbonaceous material; those in lower part mainly light reddish-brown, contain sparse carbonaceous material	Commonly crops out as alternating series of steep slopes and benches. Sandstone to mudstone ratio ranges between 1:1 and 2:1; higher ratios bear no relation to structural features, occur in northwest part of district where most of known uranium-vanadium deposits occur. Thickest in Disappointment syncline, thinnest on Dolores anticline
	Junction Creek sandstone	20–150	Light-buff fine-grained sandstone with sweeping crossbeds in south part of district. Changes northward to light reddish-brown fine-grained horizontally bedded sandstone, seems to merge with Summerville formation	Restricted to southern part of district

TABLE 1—*Continued*

Age	Formation and member	Thickness in feet	Character	Distribution and remarks
Late Jurassic	Summerville formation	60–140	Reddish-brown horizontally bedded sandy siltstone; locally near top has layers of limy nodules parallel to bedding	Forms smooth slope interrupted by thin sandstone ledge in upper part
	Entrada sandstone	90–150	Fine-grained moderately to well-sorted light-brown, light reddish-brown sandstone	Crops out as conspicuous smooth cliff in Dolores River and tributary canyons
Late and Middle Jurassic	Carmel formation	30	Reddish-brown very fine grained silty sandstone; near base contains coarse reworked Navajo sandstone, thin limestone beds, conglomerate	Forms "humpy-faced" vertical cliff
	UNCONFORMITY			
Jurassic and Jurassic(?)	Navajo sandstone	0–400+	Fine-grained well-sorted, probably wind-deposited sandstone. In places grains coarser near top. Light brown in most of district, light reddish brown in places	Forms cliffs, broad benches. Thickest in Disappointment syncline, absent in places on Dolores anticline
Jurassic(?)	Kayenta formation	180	Purplish-gray to purlish-red siltstone and sandstone; poorly sorted, largely fluvial with interbedded shales and mudstones, local conglomerates	Crops out in series of steep closely spaced cliffs
Late Triassic	Wingate formation	170–270	Very fine to fine-grained, generally well-sorted, probably wind-deposited sandstone; light buff in Summit Canyon, light reddish brown in Dolores River Canyon	Forms a sheer cliff. Contact with underlying Chinle formation is gradational; change in lithology takes place by gradual upward thickening and coarsening of individual siltstone beds; slight angular discordances present at base. Thickest in west part of district, thins eastward

TABLE 1—*Continued*

Age	Formation and member	Thickness in feet	Character	Distribution and remarks
Late Triassic	Chinle formation	490–620	Fluvial reddish-brown siltstone and greenish-gray shale, sandstone, and conglomerate. Divided into five units. Unit 5 at top composed of siltstone; averages 165 feet thick. Unit 4 composed of siltstone with thin beds of dark greenish-gray conglomerate; averages 240 feet thick. Unit 3 composed of interbedded lenses of dark brownish-red to dark greenish-gray sandstone and conglomerate; from 3 to 20 feet thick. Unit 2 composed of greenish-gray shale with minor reddish-brown shale and greenish-gray sandstone and conglomerate; averages 70 feet thick. Unit 1 composed of lenses of greenish-gray sandstone and conglomerate, slight angular unconformity with Cutler formation, averages about 50 feet thick	Crops out as steep slope broken by few ledges of resistant siltstone, lower slope broken by two receding sandstone and conglomerate cliffs. The Temple Mountain, Shinarump, Monitor Butte, and Owl Rock members, found elsewhere on Colorado Plateau, are not present in district. Unit 1 is probably Moss Back, unit 2 possibly facies of Petrified Forest or part of Church Rock, units 3, 4, and 5 lithologically similar to and likely equivalents of Church Rock
			UNCONFORMITY	
Permian	Cutler formation	1,930	Brownish-red, brownish-orange, and light-brown arkosic sandstone, siltstone, and shale	Upper 240 feet exposed in bottom of Dolores River Canyon; crops out as series of closely spaced receding ledges with indentations caused by erosion of softer beds
Pennsylvanian and Permian (?)	Rico formation	710	Brown to brownish-red and gray very fine to medium-grained sandstone, siltstone, shale, and gray very fine to fine-grained fossiliferous limestone	Marks transition from marine deposits to overlying continental deposits

TABLE 1—*Continued*

Age	Formation and member		Thickness in feet	Character	Distribution and remarks
Pennsylvanian	Hermosa formation	Upper limestone member	1,270	Light- to dark-gray very fine to fine-grained fossiliferous limestone, contains some grayish-green sandstone, siltstone, and shale near top	
		Paradox member	2,000–4,300	Dense dark-gray anhydrite, gray to light-gray punky and powdery anhydrite, fine- to medium-grained clear and gray halite, some gray halite containing inclusions of anhydrite, minor gypsum; some dark-gray carbonaceous shale	Thickest on Dolores anticline
		Lower limestone member	180	Gray fine-grained limestone	
	Molas formation		100	Reddish-brown and greenish-gray shales	
UNCONFORMITY(?)					
Mississippian and Devonian(?)	Leadville and Ouray(?) limestones undifferentiated		240	Gray fine-grained limestone	

long narrow block between two of these faults has formed the Glade graben.

A major set of fractures is oriented parallel to the principal faults in the district; a less prominent set approximately parallels the fault zone normal to the Dolores fault zone.

Sandstone dikelets in the Navajo sandstone along fractures striking about N 30° W in the area of the Dolores fault zone, may have formed when the Navajo was partly unconsolidated, suggesting initiation of fracturing in Early Jurassic time. At least two stages of fracturing are shown in the district; some fractures predate epigenetic alteration of the rocks and have controlled the alteration, whereas some postdate epigenetic alteration.

SEDIMENTARY PETROLOGY

Some accessory heavy minerals in the rocks exposed in the Slick Rock district contain appreciable amounts of some of the elements known in the ore deposits in the Morrison formation. Rocks of Late Cretaceous age con-

tain traces of elements that may be related to the advent of volcanism in the region of the Colorado Plateau near the end of the Cretaceous period.

All the clastic sedimentary rocks in the Slick Rock district older than the Mancos shale and younger than the Rico formation contain several hundredths to a few tenths of a percent of heavy detrital minerals including zircon, tourmaline, and leucoxene. Some of the rocks contain traces of garnet, staurolite, and rutile. Heavy minerals that are authigenic in most of the rocks include carbonates, leucoxene, barite, and anatase. All the reddish rocks in the stratigraphic sequence contain in the order of a tenth of a percent of black opaque

FIG. 2. Map of the Slick Rock district showing major structural features and amount of copper in uranium-vanadium deposits, San Miguel and Dolores Counties, Colo.

minerals including hematite, magnetite, and ilmenite. These black opaque minerals constitute about half of the total heavy minerals in the rocks. Almost all the light-gray, greenish-gray, and light-brown rocks in the stratigraphic sequence contain little if any ilmenite, magnetite, and hematite, but do contain pyrite, or limonite that has probably been altered from pyrite. These light-colored rocks have about half as much total heavy mineral content as do the reddish rocks.

Black opaque heavy minerals in reddish rocks of the Morrison formation average about 0.017 percent copper, 0.004 percent lead, 0.006 percent nickel, 0.13 percent vanadium, 0.24 percent chromium, 0.20 percent zirconium, and 0.019 percent niobium. Magnetites commonly contain vanadium, and as much as 4.84 percent vanadium in magnetite has been reported (8, p. 702). Spectrographic analyses of black opaque heavy minerals from reddish rocks of the Morrison formation have not detected uranium and two fluorometric analyses show less than 0.001 percent uranium in these minerals. However, some vanadium-rich ilmenites contain a few tenths to several percent uranium as well as lead, chromium, zirconium, and other elements (2, 5, 6), and vanadiferous magnetite is reported to contain uranium (R. G. Coleman, written communication, 1956). Some nonvanadiferous ilmenites contain a few hundredths to 0.20 percent U_3O_8 (8, p. 537). It is possible that black opaque heavy minerals in places in reddish rocks of the Morrison contain a few hundredths of a percent uranium.

Spectrographic analyses of many samples of pyrite separated from the Mancos shale show that pyrite from rocks about 300 feet above the base of the Mancos, at the base of the Later Carlile fossil zone, contains anomalously high amounts of metallic elements including copper, chromium, silver, gold, zinc, tin, vanadium, yttrium, nickel, and zirconium. The trace element content in pyrite decreases upward from that horizon, and pyrite about 600 feet above the base of the formation contains about the same amount of the metallic elements as does pyrite in the lower 300 feet of the Mancos.

ROCK ALTERATION

Color differences in the sedimentary rocks of the Slick Rock district are related to the position of the uranium-vanadium deposits. At least four types of postdepositional changes that involve color differences have taken place; two of these changes are thought to be diagenetic and two are considered epigenetic.

One type of change that is considered to be diagenetic took place where sediments were deposited in an oxidizing environment in which no carbonaceous material was present. Detrital magnetite and ilmenite were partly oxidized to form hematite and leucoxene respectively. Iron was redistributed and redeposited as hematite coatings on sand grains and clay fragments, imparting a reddish color to the rocks. This change probably brought the "red beds" as such into being (Fig. 3; see also 7).

A second type of diagenetic change took place under reducing conditions where abundant carbonaceous material was deposited with the sediments.

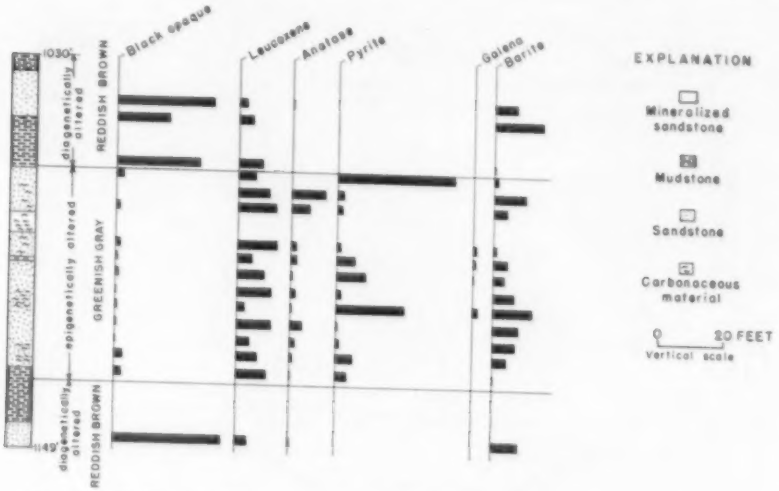


FIG. 3. Drill log showing relative abundances of some heavy minerals in greenish-gray epigenetically altered and reddish-brown diagenetically altered rocks, Morrison formation, Slick Rock district, San Miguel and Dolores Counties, Colo.

Magnetite and ilmenite were partly destroyed, and pyrite apparently developed in places from the liberated iron. Sedimentary rocks formed in this environment are light greenish gray to gray in color (Fig. 4).

A third type of postdepositional change was epigenetic. It consisted of almost complete destruction of magnetite, ilmenite, and hematite (including hematite coatings on grains), and entailed formation of pyrite from liberated iron and recrystallization of barite and leucoxene. Rocks affected by this epigenetic alteration are light greenish gray to gray (Figs. 3, 7). They are similar in gross aspect to light greenish-gray to gray rocks formed where abundant carbonaceous material was deposited. For convenience in mapping, the two types have been grouped and called "altered" rocks.

The epigenetic alteration described above is associated with at least two major structural features in the Slick Rock district. It is found in rocks within and near the Dolores fault zone, and occurs along the axial part of the Dolores anticline, in the upper part of the Entrada sandstone and adjacent to joints in sandstone of the Entrada and Salt Wash (Fig. 5).

A fourth type of postdepositional change took place where "altered" rocks were exposed to weathering. The epigenetic change resulted as pyrite oxidized to limonite; light greenish-gray to gray rocks became light brown to buff.

GEOLOGIC HISTORY

Little is known of the Precambrian history of the Slick Rock district, but the area was probably base-leveled by Paleozoic time. The first known sedi-

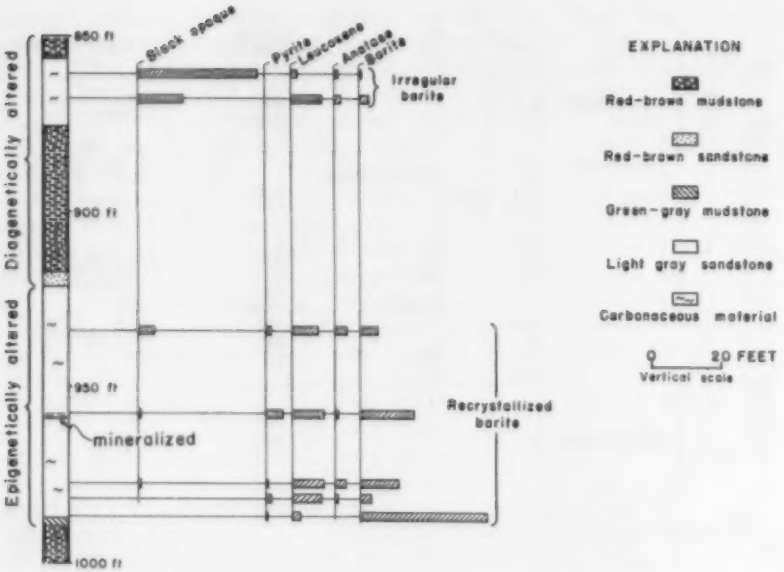


FIG. 4. Drill log showing relative abundances of some heavy minerals in light-gray epigenetically and diagenetically altered rocks, Morrison formation, Slick Rock district, San Miguel and Dolores Counties, Colo.

ments—carbonate rocks of the Ouray (?) (Devonian?) and Leadville (Mississippian) limestones and the arenaceous Molas formation (Pennsylvanian)—were deposited in a shallow sea. With development of the Paradox Basin during the Pennsylvanian period, carbonate and evaporite rocks of the Hermosa formation were deposited, followed by the coarse clastic rocks of the Cutler formation of Permian age.

From Early Triassic into Late Cretaceous time fluvial deposition predominated in the region around the Slick Rock district. During this time the Dolores anticline was periodically folded, acquiring several hundred feet of structural relief relative to the Disappointment syncline. Folding was accelerated during or shortly after the deposition of the Navajo sandstone and again during the deposition of the Morrison and Burro Canyon formations. Faulting and fracturing along the Dolores fault zone probably began during one of these periods of accelerated folding of the Dolores anticline.

In Late Cretaceous time gradual encroachment of the sea covering eastern Colorado brought a change in sedimentation, and clay size material was deposited to form the Mancos shale. Periodically during early Late Cretaceous time volcanic ash falls from volcanic eruptions in the San Juan and Rocky Mountains to the east of the district were buried in the Mancos shale. By the end of deposition of the Mancos, structural relief between the Disappoint-

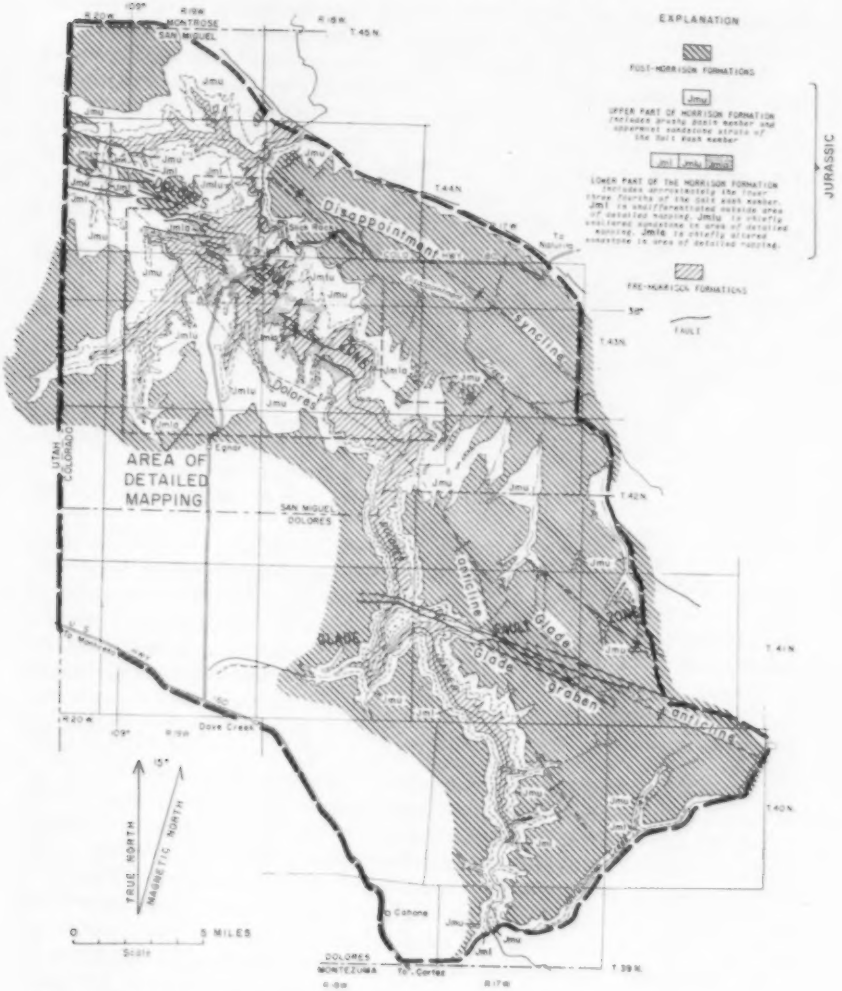


FIG. 5. Simplified structure and geologic map showing the Morrison formation, Slick Rock district, San Miguel and Dolores Counties, Colo.

ment syncline and the Dolores anticline was probably at least 1,500 feet at the horizon of the Cutler and Chinle contact and more than 1,000 feet at the top of the Salt Wash member of the Morrison formation.

At the start of Later Carlile time, during deposition of the Mancos, unique and numerous volcanic eruptions, possibly submarine, may have introduced

abnormal amounts of several heavy metals into sea water. These elements apparently were precipitated in diagenetic pyrite forming in the Mancos.

After deposition of the Mancos shale several thousand feet of sedimentary rocks of the Mesaverde, Wasatch, and Green River formations, or their equivalents, of latest Cretaceous and Eocene age probably were deposited in the district. Erosion, accompanied by a recurrent rise of the Dolores anticline and a second period of faulting and fracturing, possibly started near the middle of the Tertiary. During the last part of the Tertiary and in Pleistocene time an additional 2,000 feet of structural relief developed between the Dolores anticline and the Disappointment syncline.

Near the close of the Tertiary period and during the Quaternary period a variety of surficial deposits were layed down in the district.

STRATIGRAPHIC AND AREAL DISTRIBUTION OF THE URANIUM-VANADIUM DEPOSITS

Most of the known uranium-vanadium deposits in the Slick Rock district are in the Salt Wash member of the Morrison formation. Scattered deposits occur in the Brushy Basin member of the Morrison and in the lowest unit of the Chinle formation. The topmost sandstone unit of the Salt Wash is the principal ore-bearing horizon.

Most of the known ore deposits are in the north part of the Slick Rock district in a belt called the Dolores ore zone, which trends about N 55° W. The zone is about 20 miles long, 10 miles wide near the northwest corner of the district, and narrows to about 2 miles in width southeastward. It lies within, and normal to, the southern end of the Uravan mineral belt as defined by Fischer and Hilpert (4). The only known deposits in the district outside the Dolores ore zone are small deposits along the Dolores River Canyon east of Dove Creek and newly discovered deposits west of Egnar. Within the Dolores ore zone are narrower zones to which the ore deposits are confined; these zones are a few thousand feet wide and generally trend about N 70° W to east-west. In the Slick Rock district uranium-vanadium deposits are chiefly tabular to lenticular and parallel roughly the sedimentary bedding. Some ore bodies, however, are narrow, elongate, and curve sharply across bedding; these bodies have been called "rolls" by the miners (3) (Figs. 6, 7, 8). Tabular deposits seem to be localized in massive sandstone where clay and mudstone are interstitial, in scattered and streaked gall and pebble accumulations, and in discontinuous lenses, whereas roll deposits appear to be confined to sandstone where clay and mudstone are in numerous thin well-defined connecting layers (Fig. 6). Most of the ore deposits are in the lower part of the principal ore-bearing unit where crossbedding is more prevalent.

Narrow zones of ore deposits within the Dolores ore zone are oriented almost parallel to sedimentary trends, which average about S 70° E as shown by current lineations in the principal ore-bearing sandstone unit. Individual ore bodies within a single deposit also follow this trend.

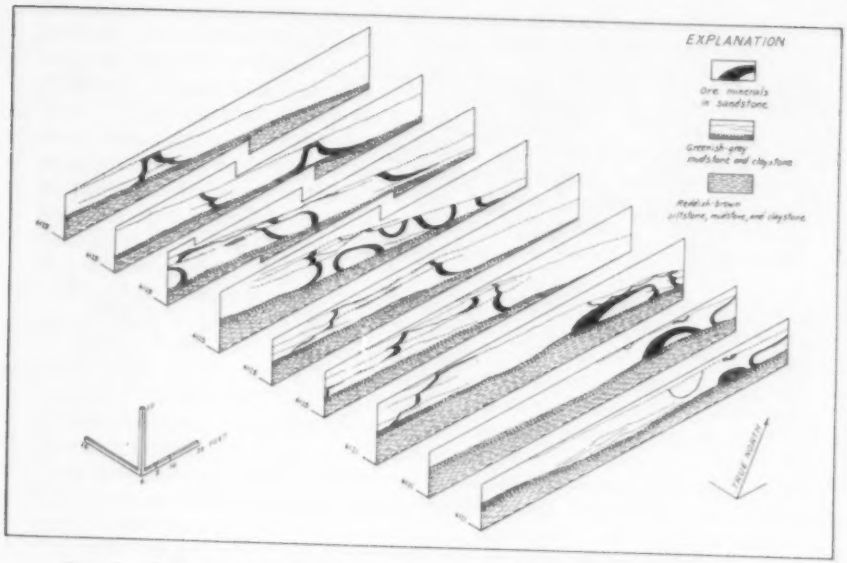


FIG. 6. Sections of roll ore bodies, west-central edge of the Cougar mine, Slick Rock district, San Miguel County, Colo.

All ore deposits occur where abundant carbonaceous material was deposited with the sediments.

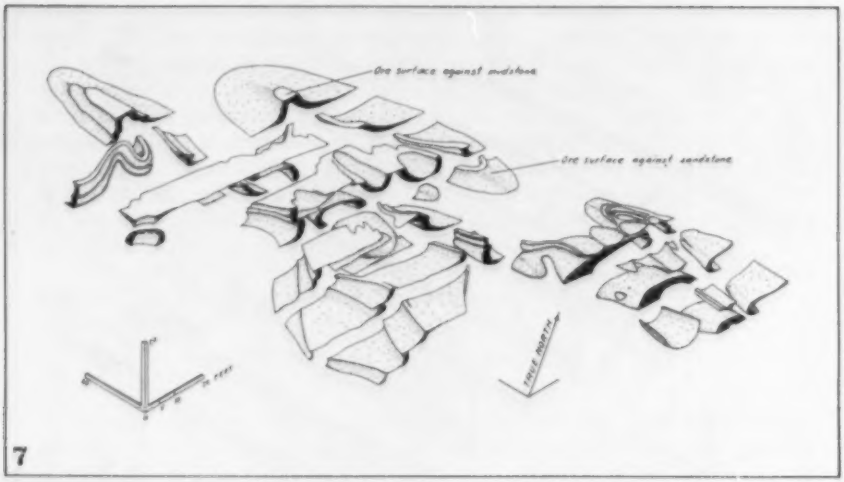
RELATIONS OF THE URANIUM-VANADIUM DEPOSITS TO STRUCTURAL FEATURES

The Dolores ore zone coincides with the Dolores fault zone and is widest where the fault zone is intersected by the northeasterly trending fault set. Ore deposits along the Dolores River Canyon east of Dove Creek lie in the Glade fault zone. Narrow zones of ore deposits within the Dolores ore zone are oriented almost parallel to the trend of principal faults and fractures in the district but do not seem to be directly associated with individual faults.

MINERALOGICAL AND CHEMICAL COMPOSITION OF THE ORES

The mineralogy of the uranium-vanadium deposits in the Slick Rock district is similar to that of deposits in other districts in the Uravan mineral belt (10). Copper-bearing minerals are more abundant in some deposits in the district than in deposits elsewhere in the belt.

Gangue minerals that have been introduced during formation of the uranium-vanadium ore bodies include carbonates and barite. Carbonate in mineralized rock appears to be more magnesium-rich than carbonate in barren rock near ore bodies. Barite in mineralized rock is pale yellow and contains



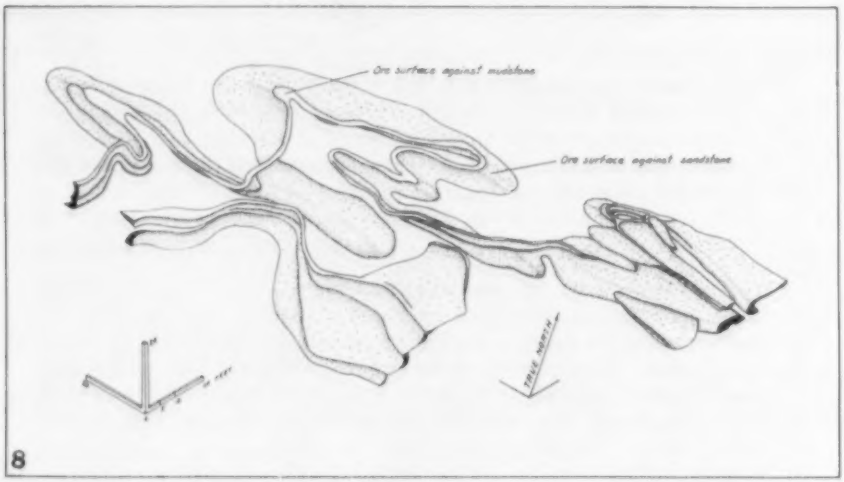


FIG. 7. Cutaway block diagram of roll ore bodies, west-central edge of the Cougar mine, Slick Rock district, San Miguel County, Colo.

FIG. 8. Perspective view of part of a roll ore deposit showing the sinuous connecting surface of the rolls, west-central edge of the Cougar mine, Slick Rock district, San Miguel County, Colo.

traces of several metallic elements, whereas barite in barren rock is colorless and contains lesser amounts of the metallic elements.

Mineral zoning is evident in some oxidized ore bodies in the Slick Rock

district, and is similar to zoning noted in some oxidized and unoxidized deposits in other parts of the Colorado Plateau. Roll ore bodies with C-shaped cross sections are paralleled by carbonate-rich zones close to the concave side of the roll, or near both sides (1). In some places a thin layer or concentric layers of goethite, altered from pyrite, are found in barren rock near the concave edge of the roll. Selenides and sulfides are concentrated in a thin layer along the concave edge of the roll. Vanadium appears to be contained largely in chlorite on the concave side of the roll, whereas it is in both chlorite and mixed layered mica-montmorillonite on the convex side (J. C. Hathaway, written communication, 1955). Barite is more abundant in the roll ore bodies than in barren rock.

Uranium-vanadium deposits mined in the Slick Rock district to date average about 0.22 percent U_3O_8, 1.7 percent V_2O_5, and 0.07 percent copper. The $U_3O_8 : V_2O_5$ ratio is about 1 : 8, slightly lower than the average of deposits in the Salt Wash sandstone member in other parts of the Uravan mineral belt. On the other hand, Slick Rock deposits are uniquely high in copper content compared to deposits in the rest of the mineral belt; some deposits in the district average as much as 0.3 percent copper. Ore deposits in the Slick Rock district also contain on the average about 0.018 percent lead, 0.0014 percent cobalt, 0.0008 percent nickel, 0.022 percent zinc, 0.021 percent arsenic, 0.0044 percent molybdenum, and less than 0.0001 percent antimony.

Neither $U_3O_8 : V_2O_5$ ratios nor amounts of uranium or vanadium show a recognizable pattern of distribution in the Slick Rock district. Copper and lead, however, are distinctly most abundant in the ore deposits within and immediately adjacent to the Dolores fault zone, and less abundant in deposits toward the edge of the zone (Fig. 2). The area of high copper and lead content is widest where the northeasterly-trending fault set intersects the Dolores fault zone, and minor copper and lead highs are situated along the northeasterly trending set southwest of the intersection of the faults. Within the Dolores ore zone selenium appears to be most abundant in deposits near the center of the zone, and less abundant southwestward in deposits along the northeasterly trending fault set. Molybdenum and some other trace elements in the ore deposits show no recognizable patterns of distribution.

Uranium and vanadium appear to have no systematic pattern of distribution within individual ore bodies. $U_3O_8 : V_2O_5$ ratios may range, seemingly haphazardly, from 1 : 1 to 1 : 20 within individual ore bodies. On the other hand, copper, lead, and selenium are distinctly high in barren rock just adjacent to the concave edge of roll ore bodies, reflecting the zonal distribution of minerals in the rock.

ORE DEPOSITS AND ASSOCIATED ALTERATION

Tabular ore bodies in the Slick Rock district average about 3 feet but vary from 1 to 20 feet in thickness. They range from a few feet to about 250 feet long and contain from a few tons to several tens of thousands of tons of ore. Elongate lens-shaped tabular bodies with simple geometrical outlines are

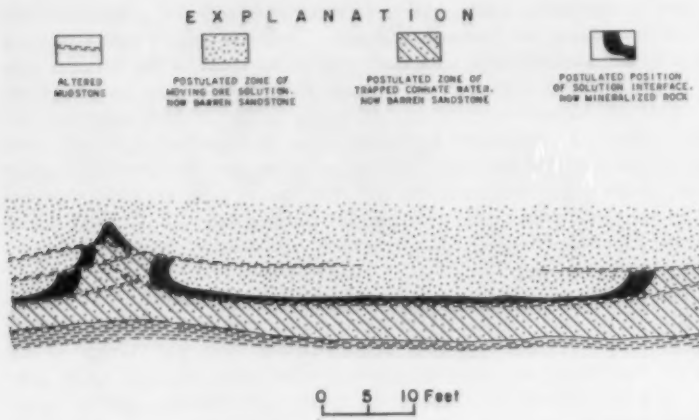

EXPLANATION
ALTERED MUDSTONE
POSTULATED ZONE OF MOVING ORE SOLUTION-NOW BARREN SANDSTONE
POSTULATED ZONE OF TRAPPED CONNATE WATER-NOW BARREN SANDSTONE
POSTULATED POSITION OF SOLUTION INTERFACE-NOW MINERALIZED ROCK
0 5 10 Feet

FIG. 9. Diagrammatic cross section of rolls in sandstone layers near the base of the ore-bearing unit of the Salt Wash member of the Morrison formation, Cougar mine, Slick Rock district, San Miguel County, Colo.

found in homogeneous sandstone, whereas more complexly shaped bodies are in heterogeneous rock.

Roll ore bodies in Slick Rock uranium-vanadium deposits range from several inches to more than 5 feet wide, a foot or so to more than 15 feet high, several feet to several hundreds of feet long, and contain a few tons to a few thousands of tons of ore (Figs. 6, 7, 8). They commonly are near and parallel to the edges of, and within, elongate sandstone lenses, and are oriented with the concave side of the roll toward the center of the lens (Fig. 9).

Uranium-vanadium deposits in the Slick Rock district occur only in sandstone that is considered to be epigenetically altered. Mudstone close to ore deposits has been extensively altered and is greenish gray, whereas mudstone in and near ore-bearing sandstone farther from deposits is largely reddish brown. The most extensive changes in epigenetically altered sandstone have occurred close to ore bodies. In barren rock on the concave side of rolls extensive solution of quartz grains and partial replacement by barite has occurred, whereas on the convex side of rolls quartz overgrowths on quartz grains are common. Authigenic anatase is appreciably more abundant immediately above some tabular ore bodies than elsewhere (Fig. 3). Minute amounts of pyrite, galena, and possibly other sulfides are more evident in the vicinity of unweathered ore deposits than elsewhere in the zones that have undergone epigenetic alteration.

ORIGIN AND GENESIS OF THE ORE DEPOSITS

The genesis of the uranium deposits in sedimentary rocks of the Colorado Plateau has been ascribed by different workers to different processes and has,

at various times, been described as syngenetic, vaguely "hydrothermal," and hypogenetic. Determination of the probable Late Cretaceous age of formation of minerals in the ore deposits (9) indicates that "penesyngenetic" processes can be excluded as a possible genesis. On the other hand, the suggestion that lead and uranium isotope abundances in the ore require that the uranium came directly from the Precambrian basement by way of leaching solutions (9) may be unreasonable. It presupposes that (1) uranite and probably galena would have been the chief sources of uranium and lead in the basement and (2) all the isotopes of uranium and lead in the basement could not pass through a sedimentary cycle and end up in the ore deposits in the ratios they are known to have. If the first assumption is true, it is likely that the second is also. It is quite possible, however, that lead and uranium in the Precambrian basement may not occur chiefly in galena and uraninite but rather in one mineral, or in two closely associated chemically and physically similar minerals, such as magnetite and ilmenite, that could survive sedimentation as detrital minerals. If this assumption is true, then there would be no way of determining by isotope frequencies whether lead and uranium in the deposits were derived from minerals in the basement or from the same minerals occurring as detritus in sedimentary rocks.

It is not likely that cooling magmas of the size and "dryness" of the Colorado Plateau laccolithic intrusions could have been accompanied by the volume of solutions required to traverse the thousands of cubic miles of rock that appear to have been epigenetically altered on the Colorado Plateau. A similar difficulty confronts the suggestion that the elements were transported by solutions from the basement to the ore deposits. A theory involving circulation of connate water through structural elements as a result of heating near igneous intrusions, leaching of elements from minerals in sedimentary rocks by the solutions, and deposition of the elements in chemically favorable locales that are a result of primary sedimentary features of the rocks is indicated by the geologic relationships observed in the Slick Rock district.

The deposition of relatively thick, laterally extensive, permeable carbonaceous sandstone in the Salt Wash member of the Morrison formation was prerequisite to the ultimate genesis of the uranium-vanadium deposits in the Slick Rock district. Of importance to the origin of the deposits was the initial presence in the sedimentary rocks of abundant black opaque detrital minerals that contained abnormally high amounts of vanadium, copper, lead, nickel, and other metallic elements including perhaps uranium.

Development of the Dolores fault zone prior to the deposition of ore provided a permeable zone that would permit extensive lateral movement of solutions through the sandstone. The advent of igneous activity in nearby intrusive centers provided a means of initiating wide-scale heating and circulation of the connate waters. Epigenetic changes in the sedimentary rocks attest to the movement of vast amounts of heated solutions, and the distribution of epigenetic alteration shows clearly the influence of structural features on movement of the solutions. Further, destruction of detrital minerals, which in unaltered rocks are known to contain many of the elements present

in the ore deposits, provided an adequate source in the sedimentary rocks for some of these elements in the ore deposits.

Spatial relationship of the Dolores fault zone with the Dolores ore zone suggests a genetic relationship of one to the other. Zoning of elements in the ores, such as copper and lead, relative to the Dolores fault zone strengthens this conclusion, and in addition suggests that copper and lead were more readily precipitated from solution than were uranium and vanadium. Uranium-vanadium ore deposits are not associated directly with individual faults, but are in a zone made more permeable by numerous faults and fractures.

Clear association of the uranium-vanadium deposits with abundant carbonaceous material in the sedimentary rocks strongly suggests that the carbonaceous material exerted a chemical influence on the deposition of ore minerals.

Roll ore bodies have formed near the impermeable boundaries at the edges of elongate permeable sandstone lenses (Fig. 9). Solution of quartz appears to have been most pronounced in the space between rolls, which occur on opposite sides of a lens, and the effects of deposition from solution are evidenced by formation of the ore minerals and barite in the rolls, and by silica overgrowths in barren rock beyond the rolls. It is concluded that deposition of ore must have occurred at an interface between moving heated connate water solutions passing through the elongate sandstone lenses and "dead" cooler connate water trapped against the impermeable edges of the sand lenses (Fig. 9). Zoning of the metals in the rolls also suggests that copper and lead were more readily precipitated from solution than uranium and vanadium. Interfaces between the ore-bearing solution and trapped "dead" connate waters must have been numerous and widespread, but ore metals were deposited only where abundant carbonaceous material provided a suitable strongly reducing environment.

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U. S. Geological Survey, Denver, Colorado,
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Aug. 18, 1958

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THE RELATION BETWEEN FRESH AND SALTY GROUND WATER IN SOUTHERN NASSAU AND SOUTHEASTERN QUEENS COUNTIES, LONG ISLAND, NEW YORK[1]

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ABSTRACT

An investigation of the geology and ground-water conditions in a part of southwestern Long Island, including the construction of 8 deep and 5 shallow test and observation wells, has been completed by the Geological Survey in cooperation with the Nassau County Department of Public Works and the New York State Water Power and Control Commission.

In this area are four main water-bearing units of Late Cretaceous and Pleistocene age. Ground water having a higher than normal salt content is encountered in some wells that penetrate the upper three units. Although the presence of this water constitutes a potential threat, existing fresh-water supplies apparently are in little immediate danger under present conditions.

The "salty" ground water has chloride concentrations ranging from about 40 to 18,000 ppm (parts per million), generally more than about 2,000 ppm. It occurs in several bodies, seaward of and beneath the fresh water in the respective aquifers, and is in contact with the fresh water through zones of diffusion. The largest salt-water body, confined under

[1] Publication authorized by the Director, U. S. Geological Survey.

artesian pressure, is in the Jameco gravel and the Magothy (?) formation beneath extreme southwestern Nassau County and adjoining southeastern Queens County. This body is thought to have occupied a substantial part of its present extent since at least 1895. It probably has been and is now encroaching, very slowly, because of increased pumping from the fresh-water bodies and possibly as a result of a postglacial rise of sea level. The rate of encroachment under present conditions probably is less than 100 feet per year.

Application of the Ghyben-Herzberg principle to compute depths to the contact between salty and fresh ground water was found to give erroneous results. More accurate depths and a clearer understanding of the relation between heads in adjoining bodies of fresh and salty ground water are obtained by use of a formula adapted from one given by M. King Hubbert.

INTRODUCTION

An investigation of the geology and ground-water conditions in southern Nassau and southeastern Queens Counties, begun in 1952, has yielded a considerable amount of new data on the relation between fresh and salty ground-water bodies in the shoreline area of southwestern Long Island. Much of the information was obtained from 13 test and observation wells called outpost wells, all but one drilled between 1952 and 1954, located at 11 sites in southern Nassau County. Of these wells, 8 range in depth from about 400 to 800 feet (deep outpost wells), and 5 range in depth from about 100 to 300 feet. Two sites have a pair of wells, 1 shallow and 1 deep. These wells were drilled and screened in artesian aquifers of Late Cretaceous and Pleistocene age.

The investigation was made by the U. S. Geological Survey in cooperation with the Nassau County Department of Public Works and the New York State Water Power and Control Commission. This paper summarizes the important geologic and hydrologic data bearing on the occurrence and movement of salty ground water, with particular emphasis on a major confined salt-water body in the southwestern part of the area. A more detailed report is being prepared by Perlmutter and Geraghty for publication by the Geological Survey.

The area investigated (Fig. 1) contains about 200 square miles. The land surface is a slightly dissected glacial outwash plain ranging in altitude from sea level at the south to about 80 feet above sea level at the north edge. In the extreme northwestern part of the area the plain abuts against a line of irregular hills, the Harbor Hill moraine. The southern margin of the plain is bordered by tidal mud flats, swamps, and shallow bays, all separated from the Atlantic Ocean by sandy barrier beaches. The surface drainage is provided mainly by 13 shallow streams, essentially all of whose discharge is ground-water outflow.

Precipitation on the area averages about 44 inches annually and is fairly evenly distributed throughout the year. Approximately half the rainfall infiltrates into the underlying geologic formations to replenish the ground-water reservoirs. In 1954, ground-water withdrawals in the area averaged about 160 million gallons daily, mainly for public supply.

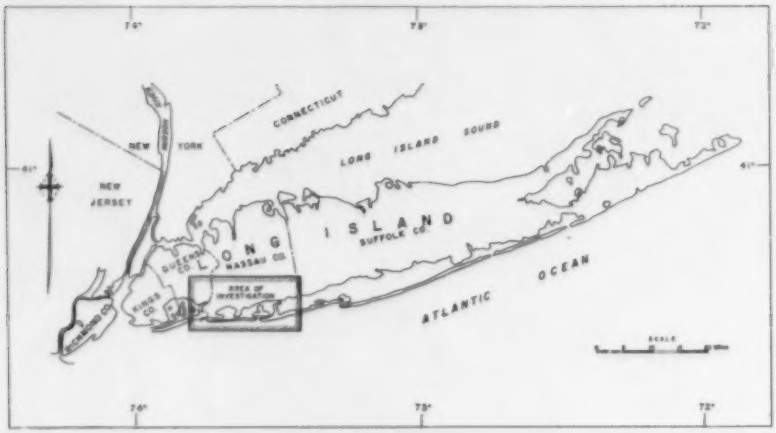

FIG. 1. Map of Long Island, N. Y., showing area of investigation.

THE GEOLOGIC UNITS

The stratigraphy and water-bearing characteristics of the geologic units underlying the area of investigation are summarized in Table 1. General geologic and subsurface contour maps of the geologic units are given by Fuller (1) and Suter, deLaguna, and Perlmutter (4). Those reports were consulted freely in preparing parts of this paper. None of the units crop out in the area except the Recent deposits and the upper Pleistocene deposits. Therefore their descriptions are based almost entirely on a study of well logs, drill cuttings and cores, and electrical logs. The eight differentiated units of unconsolidated deposits are part of the Upper Cretaceous, Pleistocene, and Recent series. The bedrock is Precambrian (?). In the vertical dimension the seaward-dipping deposits of Cretaceous age lie unconformably on the southeasterly-sloping surface of the bedrock and in turn are overlain unconformably by deposits of Pleistocene and Recent age (Fig. 2).

The combined thickness of the unconsolidated deposits ranges from about 750 feet in the northwestern part of the area to about 1,700 feet in the southeastern part.

Upper Cretaceous Series.—The Upper Cretaceous series is divided into the Raritan formation and the overlying Magothy (?) formation, both of which are composed of nonmarine beds of sand, gravel, silt, and clay. The Raritan formation is divided into two members, the Lloyd sand member below (resting on the bedrock) and an overlying clay member.

The Lloyd sand member consists of 150 to 350 feet of gray sand and gravel mixed with some clay, and lenses of clay and sandy clay. It is present beneath the entire area and presumably extends seaward some distance as a distinct unit. It is a relatively permeable aquifer and individual wells tapping it yield as much as 2,000 gpm. The water is confined, and wells along the

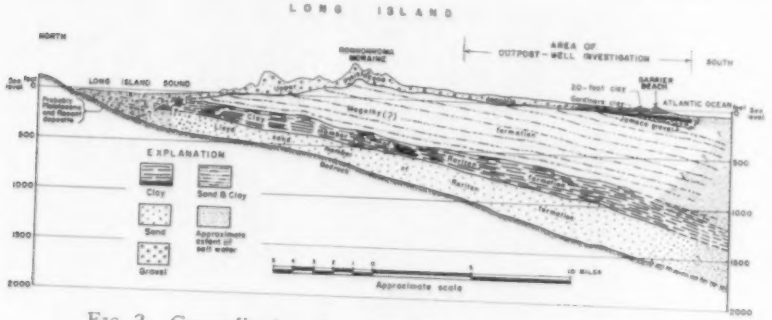

FIG. 2. Generalized section showing geologic units in central Nassau County, N. Y.

barrier beaches generally have a natural flow. In 1954 about 9.5 mgd was pumped from the Lloyd sand member in and near the project area, mainly for public supply.

The clay member of the Raritan formation ranges from about 100 to 300 feet in thickness. It consists mostly of clay and silt but contains some zones and lenses of sand and gravel and sandy clay. The colors are dark gray, red, white, and variegated. The clay member occurs throughout the area and, because it has low permeability, retards the movement of water between the Lloyd sand member and the Magothy (?) formation.

The Magothy (?) formation is the uppermost of the Cretaceous formations on Long Island. It is in part doubtless the equivalent of the Magothy formation in New Jersey; but it may also contain correlatives of other formations of Late Cretaceous age. The question mark after the name indicates this uncertainty. The Magothy (?) overlies the Raritan formation and is in turn overlain by the Jameco gravel in the southwestern part of the area, and elsewhere by outwash deposits of late Pleistocene age. The Magothy (?) formation consists chiefly of beds and lenses of gray fine to medium sand, silt, and clay; a zone of coarse sand and gravel generally is present near the bottom. The surface of the Magothy (?) is gently sloping and somewhat irregular and is trenched by valleys that extend as deep as 350 feet below sea level. The deepest valleys are in the southwestern part of the area. The Magothy (?) formation is a highly productive water-bearing unit. The water is confined, and a few wells in the southern part of the area have natural flows. The Magothy (?) formation and the overlying Jameco gravel (see below) yield about half of the water pumped in the area—about 69 mgd in 1954.

Pleistocene and Recent Series.—The principal subdivisions of the Pleistocene series from oldest to youngest are the Jameco gravel, the Gardiners clay, and the upper Pleistocene deposits. Thin bodies of sand, gravel, silt, and clay of Recent age occur along the south shore and in the bottom of the valleys of small streams.

TABLE 1

SUMMARY OF THE STRATIGRAPHY AND WATER-BEARING PROPERTIES OF THE DEPOSITS UNDERLYING SOUTHERN NASSAU AND SOUTHEASTERN QUEENS COUNTIES, LONG ISLAND, N. Y.

System	Series	Geologic unit	Thickness (feet)	Depth from land surface to top (feet)	Character of deposits	Water-bearing properties
Quaternary	Recent	Recent deposits Artificial fill, salt-marsh deposits, and shore deposits	0	0–40	Sand, gravel, clay, silt, organic mud, peat, loam, and shells. Colors are gray and brown. Restricted mainly to southern part of area.	Permeable sandy beds beneath barrier beaches yield fresh or brackish water at shallow depths. Clay and silt beneath bays retard salt-water encroachment and confine underlying aquifers.
	Pleistocene	Upper Pleistocene deposits Till and outwash	0–40	30–300	Till, composed of clay, sand, and boulders in form of terminal moraine in northwestern part of area. Outwash consists mainly of brown fine to coarse sand and gravel, stratified. In southern part interbedded with 20-foot clay.	Till, relatively impermeable, but not important hydrologically owing to limited distribution. Sand and gravel portion of outwash highly permeable; yields up to 1,500 gpm per well are reported. Specific capacities of wells range up to 109 gpm per foot of drawdown. Water generally unconfined except beneath shallow clays in southern part of area. Subject to salt-water encroachment and intermittent flooding by saline surface water near shoreline.
		20-foot clay	25–80	0–40	Clay and silt, gray and gray-green, some lenses of sand and gravel. Contains microfossils, shells, and fresh plant material. Interbedded with outwash in southern part of area. Possibly interglacial deposit.	Relative impermeable deposit. Retards salt-water encroachment at shallow depths. Serves as confining factor for water in underlying outwash and in Magothy(?) formation.
		--Unconformity?--				
		Gardiners clay	55–160 (?)	0–140	Clay and silt, gray-green, and some lenses of sand and gravel. Contains lignite, peat, shells, glauconite, Foraminifera, and diatoms. Interglacial deposit. Present beneath southern part of area.	Mainly relatively impermeable. Forms a confining layer above Jameco gravel. Lenses and perhaps channel fillings of sand provide paths for movement of water locally.
		--Unconformity?--				
		Jameco gravel	70–240 (?)	0–150	Sand, fine to coarse, dark-gray and brown, and gravel. Contains some thin beds of silt and clay. Thought to be early glacial outwash. Present beneath southwestern part of area.	Generally coarse grained and highly permeable. Yields as much as 1,300 gpm to individual wells. Specific capacities range up to 135. Contains water under artesian pressure. Water salty near shoreline. High iron content characteristic of water.

TABLE 1—*Continued*

System	Series	Geologic unit	Thickness (feet)	Depth from land surface to top (feet)	Character of deposits	Water-bearing properties
		Unconformity				
Cretaceous	Upper Cretaceous	Magothy (?) formation	40–350 (?)	30–1,000	Sand, fine to medium, gray, interfingered with lenses of coarse sand, sandy clay, silt, and solid clay. Gravel generally occurs in lower 50 to 100 feet of formation. Some sandy zones and beds of clay may be extensive. Lignite and pyrite are abundant. Present beneath entire area.	Moderately permeable. Principal artesian aquifer. Yields large quantities of water from several zones. Individual wells yield as much as 2,200 gpm. Specific capacities range up to 80. Water contained under artesian pressure; some wells in extreme southern area flow. Water generally is of excellent quality except where contaminated by salty water in southwestern part of area.
		Unconformity?				
		Raritan formation Clay member	400–1,100	100–300	Clay in solid, silty, and rarely sandy lenses, gray, white, and red. Some lenses of sand and gravel. Lignite and pyrite are abundant. Present beneath entire area.	Relative impermeable. Forms a confining zone between overlying Magothy (?) formation and underlying Lloyd sand member. Sandy zones may locally permit more rapid percolation of water. Retards but does not prevent movement of water.
		Lloyd sand member	600–1,550	150–350	Sand, fine to coarse, gray and white, and gravel; some lenses of solid and sandy clay and clayey sand. Thin beds of lignite locally. Present beneath entire area.	Generally relatively permeable. Yields as much as 2,000 gpm to individual wells. Specific capacities range up to 44. Water contained under artesian pressure; some flowing wells. Interference effects from pumping widespread. Water of excellent quality except for high iron content. No evidence of salt-water encroachment in project area.
		Unconformity				
Precambrian		Bedrock	750–1,700	—	Crystalline metamorphic and igneous rocks; schist, gneiss, and granite. Soft, clayey weathered zone at top, as much as 50 feet thick.	Constitutes impermeable floor on which water-bearing formations rest. Probably contains some water in fractures, but impracticable to develop. Not tapped by wells.

The Jameco gravel is a body of glacial outwash, composed mainly of brown sand and gravel, deposited on the eroded surface of the Magothy (?) formation in southeastern Queens and southwestern Nassau Counties. It is overlain by the Gardiners clay. The thickness of the Jameco gravel ranges from a featheredge to an estimated 180 feet in the deepest valley cut in the Magothy (?) formation. Water in the Jameco is confined.

The Gardiners clay is an interglacial deposit of marine fossiliferous grayish-green silt and clay. It lies between the Jameco gravel and the upper Pleistocene deposits in the southern part of the area. The upper surface of the Gardiners generally is 50 to 100 feet below sea level. Locally, the formation is either missing or is predominantly sandy. In particular, beds of clay do not seem to occur in much of the area south and southeast of Jamaica Bay. The absence of the clay in a few places along the shore probably affects the movement of the confined salty water in the Jameco gravel and Magothy (?) formation.

The upper Pleistocene deposits comprise three units: (1) outwash deposits, (2) 20-foot clay, and (3) till of the Harbor Hill moraine.

The outwash deposits immediately underlie the land surface in most of the area, and rest unconformably on the Gardiners clay and the Magothy (?) formation. They consist mainly of stratified beds of brown well-sorted fine to coarse sand and gravel. The outwash ranges in thickness from about 30 to 120 feet. The deposits as a whole are very permeable. In 1954, withdrawals from the outwash deposits in and near the area averaged about 70 mgd.

The 20-foot clay is interbedded with the upper Pleistocene outwash. It apparently lies beneath the shallow bays of the south shore of the area, and extends northward for 1 to 2 miles to wedge out along an irregular line. Its southern limit is unknown. The upper surface of the clay is generally about 20 feet below sea level but at places is as much as 40 feet. Accordingly, the unit has been named the 20-foot clay in this report. The unit is composed of beds of grayish-green clay and silt that commonly contain marine fossils. It ranges in thickness from a featheredge to 20 feet. Where present, it acts as a confining bed with respect to the movement of water. The 20-foot clay is older than 38,000 years, according to a recent radiocarbon age determination of shells from the clay (Meyer Rubin, U. S. Geol. Survey, personal communication) and possibly is pre-Wisconsin or early Wisconsin in age. It may be the equivalent of the interglacial Vineyard formation of Fuller (1).

The Harbor Hill moraine crosses the extreme northwest corner of the project area. It is composed largely of till—unstratified sand, gravel, clay, and boulders—which is relatively impermeable. Owing to its location, it has essentially no relationship to the occurrence or movement of salty groundwater bodies.

DESCRIPTION OF FRESH AND SALTY GROUND-WATER BODIES

In a general sense, the ground-water bodies beneath the area all are hydraulically interconnected and the formations in which they are contained can be considered a single large ground-water reservoir. However, the reservoir

comprises three particularly productive units, called aquifers, and three units that retard the movement of water, called aquicludes. The aquifers are the upper Pleistocene deposits, the Jameco gravel in combination with the Magothy (?) formation, and the Lloyd sand member of the Raritan formation. The Jameco gravel and the Magothy (?) formation together constitute the principal aquifer. The aquicludes are the 20-foot clay, the Gardiners clay, and the clay member of the Raritan formation.

Within the area the upper two aquifers contain both fresh and salty water; the Lloyd sand member contains only fresh water. Thus it is practicable to consider the ground water as consisting of several different bodies of somewhat different modes of occurrence and chemical quality. Specifically, one major unconfined fresh-water and one unconfined salt-water body have been delineated in the upper Pleistocene and Recent deposits; and one major confined fresh-water and one confined salt-water body have been delineated in the Jameco gravel and Magothy (?) formation. There is also a major confined fresh-water body in the Lloyd sand member. Finally, minor fresh- and salt-water bodies of small extent also occur at places along the shore in the upper Pleistocene and Recent deposits. These minor bodies of ground water are local in extent and are not discussed further. The major bodies of fresh and salty ground water are described in the following paragraphs.

Major Unconfined Fresh- and Salt-water Bodies in the Upper Pleistocene and Recent Deposits.—A major unconfined fresh-water body of large extent occurs in the upper Pleistocene outwash and the Recent deposits. The upper limit of this body is the water table and the lower limit is at the top of the Magothy (?) formation or the 20-foot clay. Along the northern boundary of the area the water table is about 60 feet above sea level. From there it descends, in a general southerly direction, to sea level, at a gradient of about 10 feet per mile, except locally where affected by heavy pumping. Most of the water contains less than 20 ppm of chloride, but in a few places the concentration is as much as 40 ppm. The water is harder than that in the deeper aquifers.

This unconfined fresh-water body is in contact with unconfined salty ground water along its seaward border. The contact is an irregular boundary which has not been mapped precisely but which seems to follow the edge of the salt marshes and tidal estuaries fringing the south shore. The bottom of this unconfined salty body is generally at the top of the 20-foot clay or at the top of the Magothy (?) formation. Figure 3, a north-south section near Wantagh, in southeastern Nassau County, shows an example of the occurrence of this shallow salt water. The part of the salty body shown is largely in the zone of diffusion, as the chloride concentration of the water is less than 7,000 ppm. The occurrence of the salty ground water is thought not to be the result of encroachment but to represent a natural condition common in shallow deposits bordering salty creeks, bays, and marshes.

Major Confined Fresh- and Salt-water Bodies in the Jameco Gravel and Magothy (?) Formation (the principal aquifer).—A major confined fresh-water body occurs in the Jameco gravel and Magothy (?) formation (the

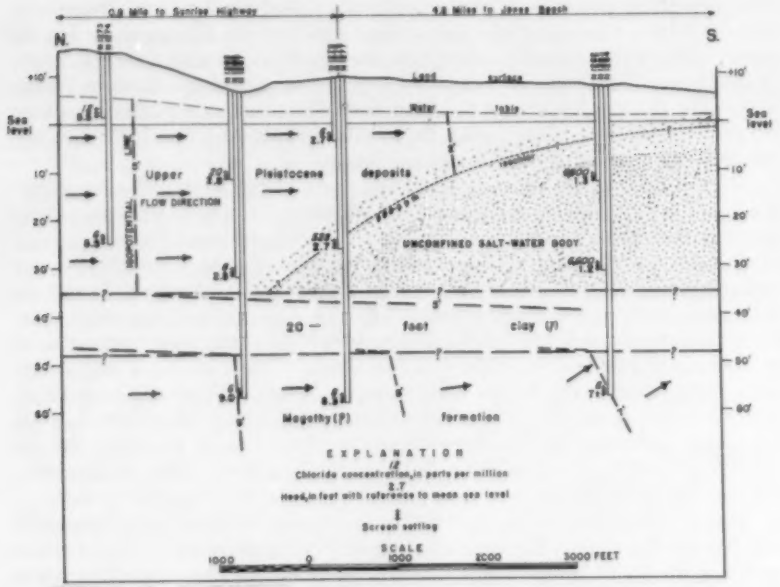

FIG. 3. Section showing relationship between fresh and salt water at shallow depth south of Wantagh, Nassau County, N. Y.

principal aquifer) in most of the project area (Fig. 4). It constitutes the principal confined water body. Its upper limit coincides with the top of the Magothy (?) formation, or the top of the Jameco gravel where present, and its lower limit with the top of the clay member of the Raritan formation. The water body has a thickness of as much as 800 feet. The water has a low mineral content and normally contains less than 10 ppm of chloride. Figure 4 shows contours on the piezometric surface of the water body in April 1954.

The shaded area on the map (Fig. 4) shows the approximate areal extent of the main confined salt-water body in the Jameco gravel and Magothy (?) formation. The salt water extends north of the shoreline in the southwestern part of the area but is entirely south of the shoreline at Jones Beach. Toward the southwest, this salt-water body occupies the full thickness of the principal aquifer, but to the northeast it wedges out on the upper surface of the Raritan clay.

Figure 5 is a section from about Hewlett, Nassau County, to Belle Harbor, Queens County, approximately along the southwestern portion of line X-X′ on Figure 4. It shows the wedgelike cross section of the main confined salt-water body and its relation to the adjacent fresh water. Chloride concentrations of water from wells screened at different depths, and data from electrical logs, were used to define the boundaries of the salt-water body. At its

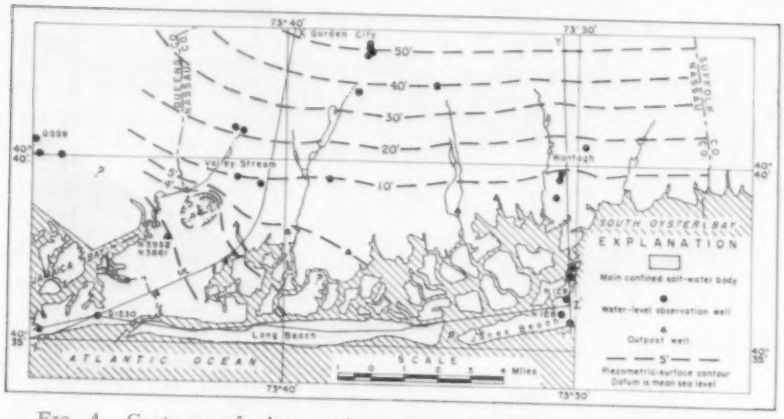

FIG. 4. Contours of piezometric surface of principal confined fresh-water body and approximate extent of main confined salt-water body in April 1954.

farthest inland extent along the line of this section, the edge of the salt-water body is about 600 feet below sea level. The boundaries of the zone of diffusion are indicated on Figure 5 roughly by the 10-ppm and 16,000-ppm isochlors. The spacing of the 10-ppm, 2,000-ppm, and 16,000-ppm isochlors shows that the rate of change of chloride concentration with depth is greater in the lower part of the zone of diffusion than in the upper part.

An east-west section through the same salt-water body is shown in Figure 6. This section shows the deep-lying main salt-water body and a shallow extension between Atlantic Beach and Lido Beach to the east. This

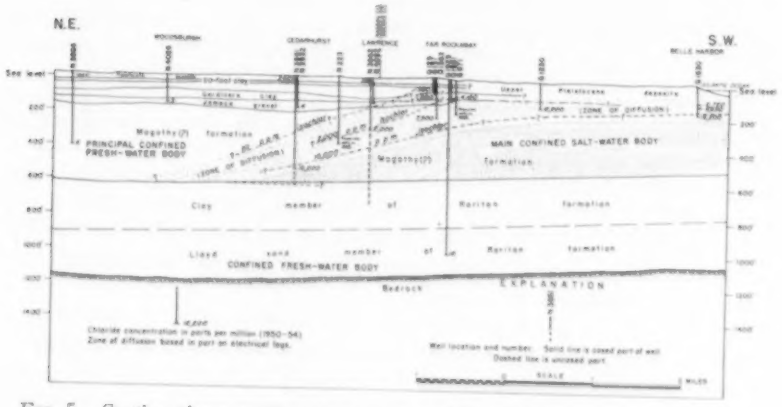

FIG. 5. Section along southwestern portion of line X-X′ on Figure 4 showing extent of main confined salt-water body and the zone of diffusion.

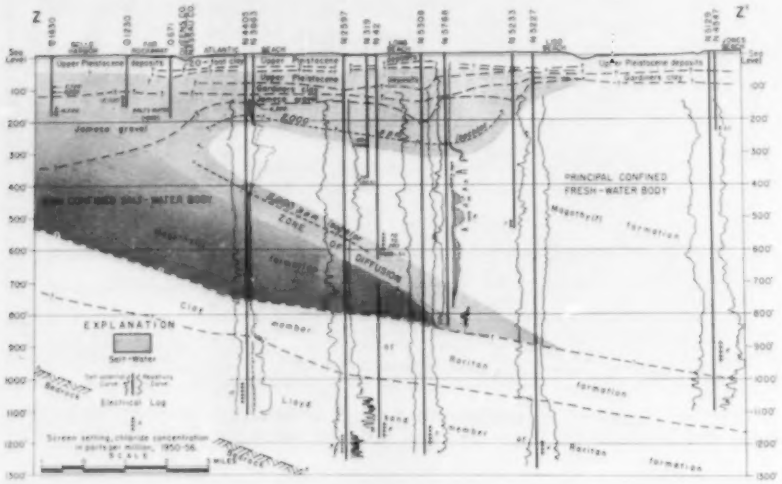

FIG. 6. Section along line Z-Z' on Figure 4 showing geologic formations and main confined salt-water body between Belle Harbor, Queens County, and Jones Beach, Nassau County, N. Y.

shallow extension is here treated as a minor prong of the deeper main confined salt-water body. Its upper surface generally is within the upper Pleistocene deposits, and its lower surface is within the Magothy (?) formation at depths ranging from about 100 to 300 feet below sea level. Chloride concentrations of water from wells screened in the shallow extension are as much as 4,300 ppm. It is significant that the occurrence of this salty body was noted at Long Beach before 1903, according to the record of well N319 (Fig. 6), at a time when withdrawals from the principal aquifer were relatively small.

The deeper portion of the main confined salt-water body shown in Figure 6 wedges out eastward along the top of the clay member of the Raritan formation about at the location of well N5227 (Lido Beach). To the west it occupies the full thickness of the principal aquifer. The chloride concentration is as much as 16,000 ppm. The zone of diffusion is indicated in Figure 6 by the lighter stippling pattern. The position of the 2,000-ppm isochlor in the zone of diffusion is estimated from known chloride concentrations and interpretation of the electrical logs.

Confined Fresh Water in the Lloyd Sand Member of the Raritan Formation.—The lowermost major confined fresh-water body is in the Lloyd sand member, between the bedrock and the overlying clay member (Fig. 6). It is tapped by relatively few wells. Most of the pumpage from the Lloyd is from deep wells on the barrier beach in southwestern Nassau County. Some

withdrawals are also made in the northwestern part of the area in Queens County.

Chloride concentrations in water in the Lloyd sand member are normally less than 10 ppm. Within the project area, the fresh water in the Lloyd sand member is not in contact with salt water. Presumably, the contact is in the aquifer south of the shoreline, but its position offshore is unknown.

MOVEMENT OF THE FRESH GROUND WATER

In the project area, which lies entirely south of the principal ground-water divide of Long Island, the general direction of movement of the fresh ground water in the principal aquifer is southward, except in the southwestern part of the area where it is southwesterly. The contours of Figure 4 represent the piezometric surface of the principal confined fresh-water body. They indicate the horizontal components of the direction of movement. In the flow sections of Figure 7 the short arrows show the vertical components of movement also. The sections are along lines X-X′ and Y-Y′ of Figure 4. Some refraction or bending of the flow lines and isopotential lines takes place where the water moves through beds of different permeability, but such irregularities are either minor or are not entirely revealed by the available data.

Section Y-Y′ illustrates the general pattern of movement of fresh ground water in southeastern Nassau County. As thus shown, the water recharged from precipitation north of the 50-foot isopotential surface moves downward and southward through the upper Pleistocene deposits into the lower part of the Magothy (?) formation and Lloyd sand member of the Raritan formation and discharges into the southern part of the bays near the shoreline and into the Atlantic Ocean. On the other hand, the water recharged within the area south of the 50-foot isopotential surface moves through the shallower beds of the upper Pleistocene deposits and the Magothy (?) formation and discharges eventually into streams and the northern parts of the bays. Note that this section shows no salty ground water in either the Magothy (?) formation or the Lloyd sand member.

The general pattern of flow in southwestern Nassau County is shown in section X-X′ (Fig. 7). The pattern of flow is similar to that in southeastern Nassau County except that it is more strongly affected by pumping. Also, the fresh water in the principal aquifer discharges over the main confined salt-water body some distance inland from the shoreline. Movement of water in the Lloyd sand member is not shown in section X-X′ but probably is in a direction about normal to the orientation of the section. The direction of movement is considerably affected by pumping.

SALT-WATER ENCROACHMENT

Salt-water encroachment is defined in this paper as the large-scale movement of salt water through an aquifer so as to displace fresh ground water bodily, either permanently or for a period of time measured in years. It excludes small-scale and temporary intrusions of salt-water tongues induced

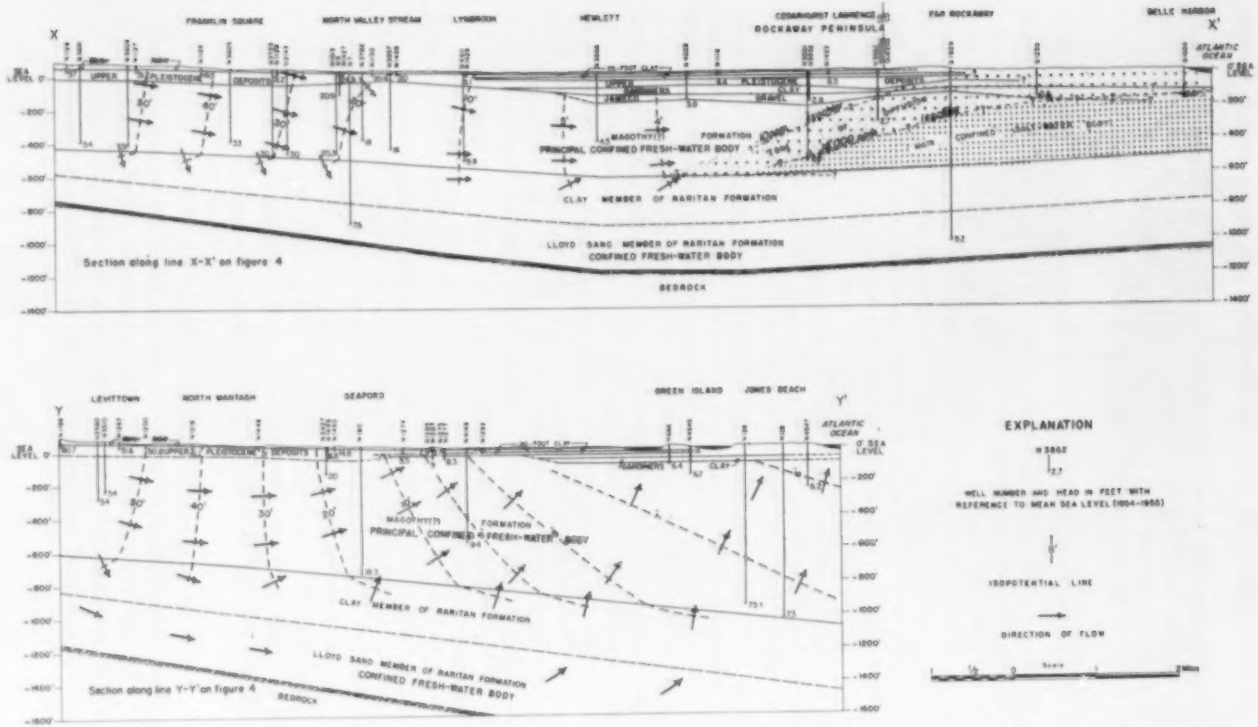

FIG. 7. Sections showing flow of water in principal confined fresh-water body in southwestern (X-X′) and southeastern (Y-Y′) Nassau County.

by local pumping from wells constructed close to an existing salt-water body. The shallow salty ground-water bodies bordering the shore present no great threat to existing public-water supplies, which are taken mainly from the deeper formations. Consequently, the following discussion of encroachment deals only with the main confined salt-water body in the Jameco gravel and Magothy (?) formation (Fig. 4).

According to early records, the main salt-water body must have occupied a substantial part of its present extent as much as 50 year ago. Reports of salty water and actual determinations of chloride concentrations in well waters in southwestern Nassau and southeastern Queens Counties are given in U. S. Geological Survey Professional Paper 44 (5). The data are for water samples taken in wells at various depths from 150 to as much as 400 feet below sea level. Although the data are scanty, they show that salt water was present in the Jameco gravel and Magothy (?) formation at least as early as 1903 in Long Beach and in Lawrence, in southwestern Nassau County, and also in Far Rockaway, Queens. Thus the salt water was present some distance inland in the principal aquifer before any heavy pumping took place, and it may have extended landward to within 1 or 2 miles of its present boundary. Thus encroachment since 1903 probably has not been more than 1 or 2 miles; therefore it is likely that the present inland extent of the salt water is only partly a result of encroachment.

Evidence bearing on the problem of encroachment of the main confined salt-water body is both direct and indirect. The direct evidence suggesting encroachment consists of increases in chloride in the water from certain wells within the past 50 years. Indirect evidence, suggesting that conditions favoring encroachment exist, consists of (1) observed net declines of fresh-water levels related to increase in pumping and (2) low heads in the adjoining confined fresh- and salt-water bodies that show or imply the existence of landward gradients in the salt water.

Observed Increases in Chloride Concentrations.—In southeastern Queens County near Jamaica Bay, increases in chloride concentrations in water from several wells have been reported or observed. In that area, the water from several public-supply wells screened in the Jameco gravel was contaminated after the wells were put into operation. For example, the water from well Q559 in South Ozone Park showed a steady increase in chloride concentration from 4 ppm in 1932 to 165 ppm in 1951, when the well was abandoned. The rate of chloride increase showed a definite steepening after 1945, although the annual withdrawals from the well were considerably reduced. This is considered to mean that the increase in chloride was not solely the result of pumping from the well, but that encroachment of salt water was taking place, albeit slowly, in the area. The actual cause of encroachment may have been increased withdrawals in central Queens to the north.

In southwestern Nassau County, the only known instance of increase in chloride is at well N42 (Fig. 6), situated on the barrier beach, which yielded fresh water initially but salted up almost immediately after being put into regular operation. This history suggests that the well had been screened

near an existing salt-water body and the high chloride concentration was not the result of regional encroachment. In southeastern Nassau County there are no records of salt-water contamination of wells screened in the principal aquifer.

Decline of Fresh-water Levels.—There is considerable evidence for overall declines of water levels in southwestern Nassau and southeastern Queens Counties since about 1895. In southeastern Queens County, for example, the water table has declined as much as 20 feet at some places since 1903. Artesian heads of the principal confined water body in southwestern Nassau and southeastern Queens are estimated to have declined 1 to 7 feet since 1895 at or near the sites of 12 wells. The average decline is about 3 feet. In this area at present the fresh-water artesian heads are 5 feet or less above mean sea level and at a number of wells are too low to balance, according to the Ghyben-Herzberg principle, a stabilized salt-water body having a density of 1.025.

From the late 1800's to the present the withdrawals increased in amount and were taken more and more from the principal confined fresh-water body. The overall declines in water levels and artesian pressure generally coincide with this increase in withdrawals in and near the area. Corresponding declines of head must have taken place also in the adjoining parts of the main confined salt-water body, thus establishing a small landward gradient in that body.

In southeastern Nassau County the increase in withdrawals has been very small in comparison with that in the southwestern part of the county. Also, the available water-level data in the southeastern part do not suggest appreciable declines in artesian heads. However, the fresh-water artesian heads in this area also are too low to balance a stabilized salt-water body having a density of 1.025 at the depth at which the fresh water actually occurs. The significance of this apparently anomalous condition is discussed in the following paragraphs.

Heads in the Salt- and Fresh-water Bodies.—At Jones Beach in southeastern Nassau County, two wells, N128 and N129, screened in the Magothy (?) formation at about 1,000 feet below sea level, tap the principal confined fresh-water body at about the same place (see Y-Y', Fig. 7). Since the installation of the wells in 1929 and 1933, respectively, the static water levels in them, according to a few intermittent measurements, have averaged about 8 feet above sea level. The chloride concentrations in the water have been 10 ppm or less. The contact between fresh and salty water in the principal aquifer is an unknown distance seaward from Jones Beach but possibly is within a mile or two of the shoreline.

According to the Ghyben-Herzberg principle, if the head of about 8 feet in the fresh-water body at Jones Beach were in balance with a stabilized salt-water body having a density of 1.025, then the fresh-salt-water contact would occur at about 320 feet below sea level. However, there is no salty water in the Magothy (?) formation at Jones Beach at least to a depth of about 1,000 feet where the wells are screened. Furthermore, if the fresh-salt-water con-

tact were at a depth of 1,000 feet the Ghyben-Herzberg principle would require a head of about 25 feet in the fresh-water wells.

The apparently anomalous data at Jones Beach are believed to indicate that heads are below sea level (negative) in the toe of the salty body offshore, and that there is a landward gradient in the salty body from points on the ocean floor where the head must be zero with reference to mean sea level. Such a landward gradient may in part reflect the influence of pumping on the fresh-water side of the contact, but it also may be due largely to a lag in response to a post-Pleistocene or late Pleistocene rise in sea level.

Evidence for a post- or late glacial rise of sea level is worldwide. Certainly there has been an overall net rise of sea level with respect to Long Island on the order of 50 to 100 feet since the deposition of the interglacial marine Gardiners clay, and of a lesser amount since the deposition of the 20-foot clay. Inasmuch as many of the deposits through which the salty water would have to move are of low permeability, encroachment would be relatively slow and might lag behind the rise of sea level.

In southwestern Nassau and southeastern Queens Counties there are direct measurements of the head in the main confined salt-water body. Water levels in well N3861, which is screened in this salty body at Cedarhurst, have ranged from about 3 to 7 feet below mean sea level during the period of record from 1952 to the present (1957). The salt water has a chloride concentration of about 16,000 ppm and a density of 1.018. Fluctuations of salt-water levels in this well are synchronous with fluctuations in nearby fresh-water wells that tap the adjacent fresh-water body. The low levels of about 7 feet below sea level occur during periods of heavy draft on the fresh water and those at 3 or 4 feet occur during periods of recovery or of light draft. During the entire period of record the water level has not been higher than about 3 feet below sea level.

Well Q1230, to the southwest, taps salt water having a chloride concentration of about 12,000 ppm. The density has not been determined, but should be about 1.013. At this well the head is about at sea level. Thus, even allowing for the small difference in density, there seems to be a small overall landward gradient in the salt-water body between well Q1230 and well N3861.

Well N3861 is south of an area where artificial withdrawals have been large and steadily growing. Thus the apparent deficiency of head may be due largely to pumping. If so, any negative head due to lag in response to rise in sea level is very small. That the negative head is not any larger is thought to mean that the movement of salt water in the formations since sea level began to rise was expedited by the presence of the highly permeable Jameco gravel, and because the overlying Gardiners clay is either missing or sandy in the area west and south of Jamaica Bay. It is believed that these geologic factors largely account for the inland position of the salty ground water reported by Veatch (1906). Since the time of Veatch's report, increased pumping has lowered fresh-water and salt-water heads and has induced some actual encroachment.

Rate of Encroachment.—In southeastern Queens County, the only indication of the rate of encroachment is the slow but steady increase in chloride concentration at well Q559. If this increase represents encroachment and not simply local contamination, the indicated rate of encroachment is very slow.

Calculation of rates of movement in the main confined salt-water body are restricted to southwestern Nassau County where estimates have been made of the regional gradient in the main salty body and of the gradient near the toe of the main salty body. The regional gradient is estimated to be roughly 1.5 feet per mile and the maximum gradient in the toe under moderate and extreme rates of pumping may be on the order of 3 to 6 feet per mile. Based on these ranges in gradient, and on the assumption of an average porosity of 25 percent and an average permeability of about 500 gpd per square foot for the Magothy (?) formation, the calculated rates of movement for gradients of 1, 3, and 6 feet per mile are about 18, 54, and 109 feet per year, respectively. The low rates probably represent the approximate rates of regional encroachment, on the assumption that all the movement represents encroachment. The highest rates may be effective in the toe near the centers of heavy pumping for a few months each year, but during the remainder of the year the rates probably are lower. If future conditions are such that withdrawals are greater and the gradients in the salt water are increased, the rate of movement will be faster.

DEPTH TO FRESH-SALT-WATER CONTACT

In the area of this investigation it has been found that computed depths to salt water based on the Ghyben-Herzberg principle do not conform to the observed depths of the fresh-salt-water contact. The Ghyben-Herzberg principle can be expressed by the formula

$$z = \frac{\rho_f}{\rho_s - \rho_f} \cdot h, \tag{1}$$

where z is the altitude in feet with reference to mean sea level of a point on a sharp interface between fresh and salt water, ρ_s is the density of the salt water, ρ_f is the density of the fresh water, and h is the altitude of the water table directly over the point on the interface.

A basic assumption of the Ghyben-Herzberg principle is that the head in the salt water is at mean sea level and that the fresh water and salt water are both static. However, in much of southern Nassau County the heads in the main confined salt-water body are below mean sea level. As mentioned previously, the heads at well N3861 at Cedarhurst have been below sea level at least since 1952. At several deep fresh-water wells in southern Nassau County heads are less than would be required to prevent salt water from occurring at the screened depths, such as the Jones Beach well, N129. The observed head deficiencies in fresh water are believed to mean that heads in the salt-water body nearby are below mean sea level, owing to complex geologic and hydrologic factors in this area.

Accordingly, calculations of depth to a fresh-salt-water contact based on an assumed head in salt water at mean sea level give erroneous results. Thus the actual heads and densities of the salt water must be considered. These are taken into account in a modification of formula (1) which includes factors for head and density of the salt water as well as of the fresh water (2, p. 864, 3, p. 1991).

The modified formula is as follows:

$$z = \frac{\rho_s}{\rho_s - \rho_f} \cdot h_s - \frac{\rho_f}{\rho_s - \rho_f} \cdot h_f, \qquad (2)$$

where z is the altitude of a point on the fresh-salt-water contact, h_s is the altitude of the water level in a well filled with salty water of density ρ_s and terminated at the contact at the depth z, and h_f is the altitude of the water level in a well filled with fresh water of density ρ_f and also terminated at the contact at the depth z. This general equation can be used either where salty ground water is encroaching (heads in the salt water are negative or below mean sea level) or where it may be receding (heads in the salt water body are positive or above mean sea level).

An application of formula (2) to data obtained in June 1952 for a pair of wells at Cedarhurst, N. Y., is given below. Although the screens of the two wells are about 350 feet apart vertically, observed data indicate that vertical flow components in both the fresh and salty water are negligible at this site (Fig. 7). A head of 6.0 feet below mean sea level in the salt-water body (density 1.018) was measured in well N3861, and a head of 2.7 feet above mean sea level in the overlying fresh-water body was measured in well N3932. Substitution of these data in formula (2) gives the following calculation:

$$\begin{aligned} z &= \frac{1.018}{1.018 - 1.000} \cdot (-6.0) - \frac{1.000}{1.018 - 1.000} \cdot (2.7) \\ &= 56.6(-6.0) - 55.5(2.7) \\ &= -489 \text{ feet.} \end{aligned}$$

In the calculation, z represents the theoretical depth below mean sea level of a contact between water of density 1.000 and water of density 1.018, assuming a sharp boundary. Obviously not all the assumptions of formula (2) are fully met by the data in the example, but nevertheless the depth computed by formula (2) does fall well within the boundaries of the zone of diffusion, which spans the interval from about 330 to 530 feet below mean sea level (Fig. 7). In contrast, substitution of the same data in formula (1) gives a computed depth to salt water of only 150 feet.

Also by using formula (2), approximately the same value for z can be calculated for any period since the start of record at Cedarhurst, suggesting relative stability or little measurable change in the position of the contact from 1952 to 1956. In contrast, calculations based on formula (1) during the

same period give an apparent wide range in z, corresponding with the observed wide range in fluctuations of the fresh-water head. Considering the large quantities of water that would have to be moved, it is highly doubtful that such large shifts of the contact actually could have taken place in the comparatively short time intervals indicated by records of water-level fluctuations.

Obviously, in applying formula (2) in situations similar to that cited, the smaller the vertical distance between the two well screens, and the narrower the zone of diffusion, the more accurate is the computed depth to the contact. If the head and density of fresh water are known at a site, and if corresponding data can be obtained or estimated from other known information for the salt water at the same site, then the depth to the contact can be estimated with fair accuracy. The main conclusions are that the depth to a fresh-salt-water contact depends on the heads and densities of both the fresh and salt water, and that, in some areas at least, serious errors can result from calculations based on fresh-water data alone.

EFFECTIVENESS OF THE OUTPOST-WELL NETWORK

Outpost wells screened in fresh water landward of a body of salty ground water provide only a small part of the data needed in studying the problem of salt-water encroachment. Outpost wells do serve to indicate whether or not salt water has arrived at the sites of the wells, and do afford a basis for recording long-term water-level fluctuations. They cannot, however, be used by themselves to indicate the direction or rate of movement of salt water. In order to estimate these, knowledge of the density of water and water levels or heads at different places and at several depths in the zone of diffusion and in the main part of the salt-water body are required, together with information on porosity and permeability of the sediments that contain the salty water.

The present outpost-well network in southern Nassau County affords information chiefly on the fresh water. Two of the wells tap salty water, but they do so at places where the chloride concentration should change not at all or very slowly, and several tap fresh water immediately above the zone of diffusion. The other wells are some distance landward from the present salt-water contact and salt water could not be expected to arrive at them for many years.

The experience gained in this investigation suggests that the two basic elements in the analysis of a salt-water-encroachment problem are (1) the landward extent of salt water, and (2) the rate and direction of movement of the salt water. The first element can be obtained from exploratory holes of small diameter in which electrical logs can be run. The second can be obtained by constructing test and observation wells near the toe of the salty wedge in which changes in chloride concentration could be observed; and also at various depths and places within the salt water so as to map the heads and determine the hydraulic gradients in the salt-water body.

Where a salt-water body lies entirely offshore and there is reason to believe that it is encroaching, obviously there is no alternative except to construct outpost wells at or beyond the shoreline as a preliminary measure.

U. S. GEOLOGICAL SURVEY,
MINEOLA, N. Y.,
Sept. 1, 1958

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GEOLOGY OF THE RAINY DAY URANIUM MINE, GARFIELD COUNTY, UTAH[1]

EDWARD S. DAVIDSON

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ABSTRACT

The Rainy Day mine, in the Circle Cliffs area, Utah, is developed on a long slender pod of uranium ore. Ore is localized in siltstone of the Moenkopi formation of Triassic age, on the south edge of a channel about 3,300 feet wide by 40 feet deep that is filled with sandstone of the Shinarump member of the Chinle formation of Triassic age. Shale of the Chinle rests directly on siltstone of the Moenkopi on either side of the channel. The pod of ore is of moderately high grade, 1½ by 4 feet in cross section, and is continuous for a mined distance of more than 1,800 feet. Sphalerite, chalcopyrite, pyrite, marcasite, and galena are associated with a black uranium mineral, which is probably uraninite. Semiquantitative spectrographic analyses show that lead, copper, nickel, cobalt, silver, molybdenum, zinc, yttrium, and ytterbium increase proportionately with uranium; the increase suggests that these metals were introduced by the ore-forming fluid.

The deposit is on the east flank of the northwest-trending Circle Cliffs anticline. No major faults are near the mine, nor were any throughgoing joints noted in the deposit. Efforts to correlate the localization of the deposit with minor structures were unsuccessful.

INTRODUCTION

THE Rainy Day uranium mine is in the eastern part of the Circle Cliffs area, about 45 miles southwest of Hanksville, Utah (Fig. 1). The mine was opened in the spring of 1954 and was operated more or less continuously until the fall of 1955. It was reopened in the spring of 1956, and was operated on a small scale during 1956 and 1957.

The deposit is unusual in that it is not more than 6 square feet in cross section, yet it is continuous for more than 1,800 feet along its strike. The

[1] Publication authorized by the Director, U. S. Geological Survey.

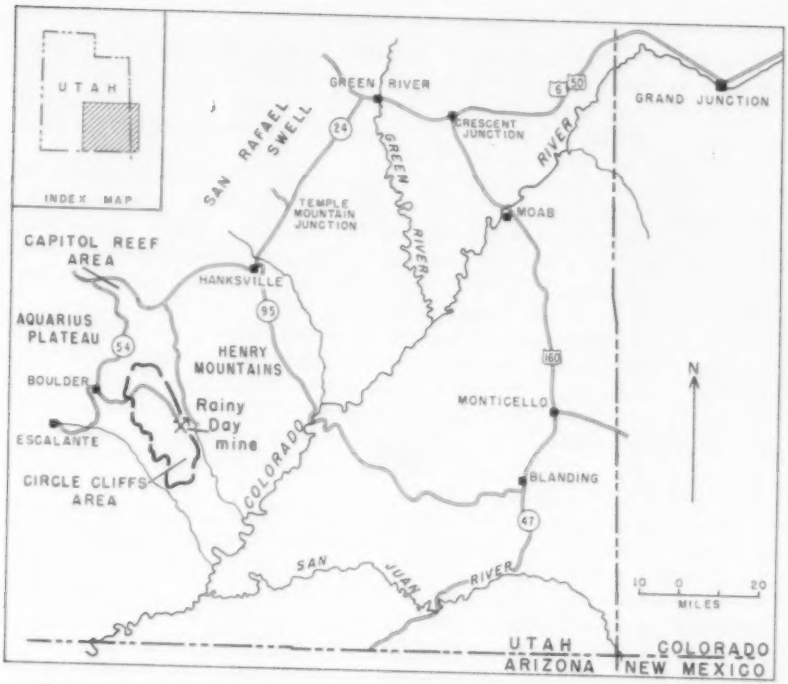

FIG. 1. Index map of southeastern Utah, showing location of the Rainy Day mine.

uranium ore is localized in siltstone and mudstone of the Moenkopi formation of Triassic age, on the south side of a channel filled with sandstone. This is in contrast to most "channel type" uranium deposits in rocks of Triassic age, which are localized in the channel filling sandstone.

This report describes the relation of the uranium deposit to the local geology and presents several analyses of ore and subore that show similarities between this deposit and those in the Shinarump and Moss Back members of the Chinle formation of Triassic age.

Field work was done in the summers of 1954 and 1955 in connection with the geologic mapping of the Circle Cliffs area by the U. S. Geological Survey on behalf of the Division of Raw Materials of the U. S. Atomic Energy Commission. All geologic contacts were mapped in the field on a topographic base map at a scale of 1 inch equal to 2,000 feet and with a 40-foot contour interval. The writer was ably assisted in the field by Louis D. Carswell and David A. Brew of the U. S. Geological Survey. This report received critical review by members of the U. S. Geological Survey staff in Grand Junction, Colo., especially Richard P. Fischer to whom special thanks are due.

GENERAL GEOLOGY

The Circle Cliffs is a breached anticline; rocks of Permian and Triassic age floor the interior, which is about 10 by 30 miles across and rimmed by cliffs of resistant sandstone of Triassic and Jurassic age. Gregory and Moore (3), Hunt (8), and Steed (12) have described the geology of the area. The following is a brief resumé.

The oldest rock exposed in the vicinity of the Rainy Day mine is of Permian age and is sandstone with medium- and large-scale crossbeds. The base of this sandstone is not exposed, but 105 feet of it crops out in a canyon a few miles south of the Rainy Day mine. The sandstone is correlated with the Coconino sandstone by Gregory and Moore (3, p. 45) and with the White Rim member of the Cutler formation by Steed (12, p. 100–101).

A white to light-yellow flat-bedded sandstone overlies the cross-bedded sandstone. Fine-grained friable white sandstone and dolomite-cemented light-yellow sandstone are the main constituents although a few sandy dolomite beds are present. This sandstone ranges from 50 to 75 feet in thickness and was probably included in the Kaibab limestone by previous workers (3, 8, and 12). The top of this sandstone was used for structural control in the vicinity of the Rainy Day mine (Fig. 2).

The Kaibab limestone of Permian age conformably overlies the flat-bedded sandstone. The formation consists of light yellowish-white dolomite in beds ranging from 1 to 4 feet thick. The top of the Kaibab is an erosional surface. In most places the formation is about 45 feet thick, but in a few places the Kaibab has been completely removed by erosion.

The Moenkopi formation of Early and Middle (?) Triassic age is composed mainly of sandstone, siltstone, and mudstone, but some dolomitic units form the base of the formation and several persistent dolomitic (?) siltstone beds occur near the top of the formation. The Moenkopi is dominantly reddish brown in color. The lower part of the formation, however, weathers gray or light yellow in the central and eastern parts of the Circle Cliffs; the fresh rock in these places is petroliferous and is gray or black in color. Also, the upper few feet of the Moenkopi, where overlain by the Shinarump member of the Chinle formation, is locally dark to light gray, weathering on the outcrop to light yellow. The gray color, according to Keller and Schultz (9), is caused mainly by reduction of the ferric iron in the red siltstone to ferrous iron, a process that may be due to chemicals included in ground water. Data presented later in this report indicate that the color change, in the Rainy Day mine area at least, is also accompanied by a decrease in amount of iron present in the gray rock. This formation ranges from 475 to 525 feet in thickness.

The Chinle formation of Late Triassic age is divided into several members in the Circle Cliffs area. The lowest member, the Shinarump (13), is described in detail below. The other members, which are not described in detail, are composed of varicolored red, gray, and purple bentonitic and nonbentonitic mudstone, siltstone, and sandstone and minor limestone; they range in combined thickness from 600 to 700 feet.

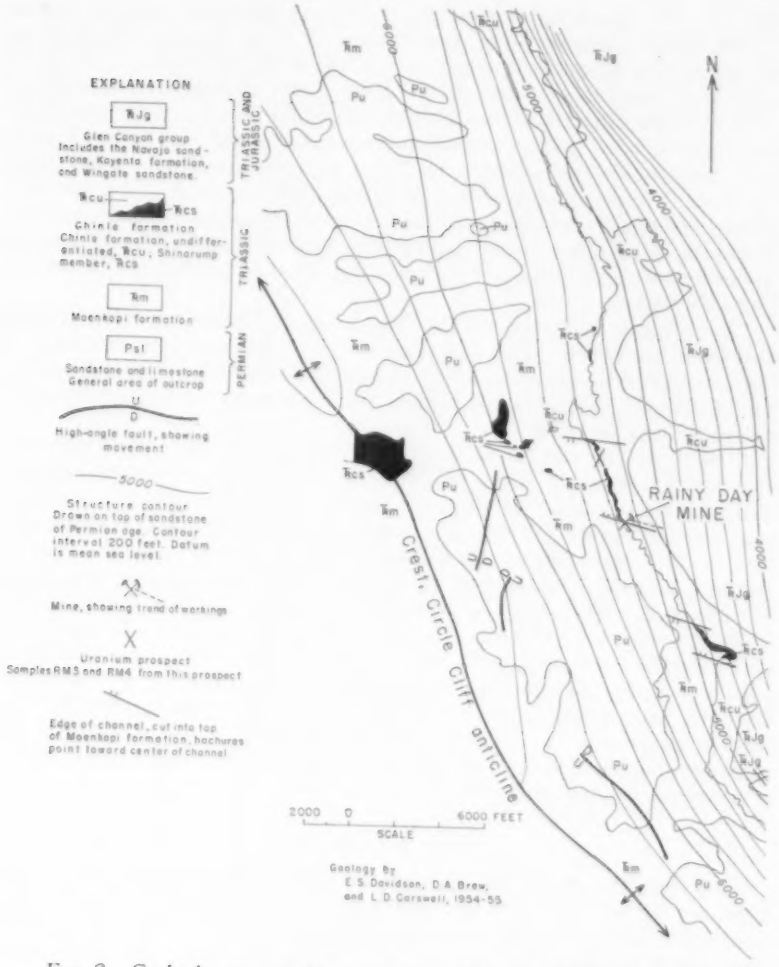
EXPLANATION
TRJg
Glen Canyon group includes the Navajo sandstone, Kayenta formation, and Wingate sandstone.
TRCu
TRCs
Chinle formation Chinle formation, undifferentiated, TRCu; Shinarump member, TRCs
TRm
Moenkopi formation
Psl
Sandstone and limestone General area of outcrop
U
D
High-angle fault, showing movement
5000
Structure contour Drawn on top of sandstone of Permian age. Contour interval 200 feet. Datum is mean sea level.
Mine, showing trend of workings
X
Uranium prospect Samples RM3 and RM4 from this prospect
Edge of channel, cut into top of Moenkopi formation, hachures point toward center of channel
TRIASSIC AND JURASSIC
TRIASSIC
PERMIAN
N
RAINY DAY MINE
Crest, Circle Cliffs anticline
2000 0 6000 FEET
SCALE
Geology by E. S. Davidson, D. A. Brew, and L. D. Carswell, 1954-55

FIG. 2. Geologic map of the area surrounding the Rainy Day mine.

The Shinarump member is a fine- to medium-grained white feldspathic sandstone with some interbedded gray micaceous mudstone. It is commonly 40 to 60 feet thick in most of the Circle Cliffs area, and may be considerably thicker where it fills Triassic stream channels cut in the underlying Moenkopi formation. In the vicinity of the Rainy Day mine, the Shinarump is mostly absent. It crops out in very small areas in the eastern part of the area shown on Figure 2 and occurs on isolated mesas in the western part.

The two outcrops in the eastern part of the area are interpreted as deposits in two stream channels. The northernmost of these channels, along which the Rainy Day deposit is localized, is 3,000 to 3,400 feet wide and the sandstone is not more than 40 feet thick. Most of this thickness is gained at the expense of the Moenkopi formation although in the outcrop on the cliff there appears to be some buildup of sandstone over the central part of the channel. The sandstone deposit to the south fills a channel that is only about 1,200 feet wide, but here the sandstone is almost 100 feet thick. Uranium and copper minerals are localized near the contact of the Shinarump member and Moenkopi formation in both channel deposits, but exploration in parts of these channel deposits has not disclosed any uranium ore except that in the Rainy Day mine.

The Wingate sandstone of Late Triassic age is a light-orange fine-grained well-sorted sandstone. This sandstone is 230 to 350 feet thick and forms a cliff that caps the escarpment for which the Circle Cliffs is named. The contact between the Wingate sandstone and the Chinle formation is disconformable but with negligible relief.

The Rainy Day mine is on the eastern flank of the Circle Cliffs anticline. The anticline trends N. 30° to 35° W., and pitches southeast in the southern part of the area shown on Figure 2 and to the northwest in the northern part; maximum pitch is 1½° to 2°. On the northeastern side of the anticline, dips in the central part of the anticline increase gradually to 15°; dips on the flank increase abruptly from 15° to 50°. Beds near the mine dip about 12° northeast. The structural surface illustrated on Figure 2 is represented by lines drawn through points of equal elevation on the top of the sandstone that underlies the Kaibab limestone. North and east of the mine, this sandstone is not exposed and the contours below about 5,200 feet are projected from the base of the Wingate sandstone. This projection is supported by three complete and two partial measured sections and was constructed by assuming that the folding is of the parallel type, so that stratigraphic thickness remains constant downdip.

RAINY DAY DEPOSIT

The mine was opened on the northwest end of a long slender pod of uranium ore 1½ feet by 4 feet in cross section by 1,800 feet in length. The main drift, which followed the ore pod, trends about N. 70° W. at the westernmost end of the mine, and about N. 85° W. in the eastern end of the mine and slopes about 9° southeast (Fig. 3). Several exploratory crosscuts and inclines have been driven to the northeast into the sandstone of the Shinarump member of the Chinle formation and along the Shinarump and Moenkopi contact, but encountered no additional ore, although the siltstone of the Moenkopi formation directly underlying the contact is noticeably more radioactive than normal. Exploration of other parts of the channel has found no rock of commercial grade, but high radioactivity and copper staining are evident in the siltstone of the Moenkopi near the contact with the Shinarump. Locally, abundant pyrite is found in the lower foot or so of the Shinarump.

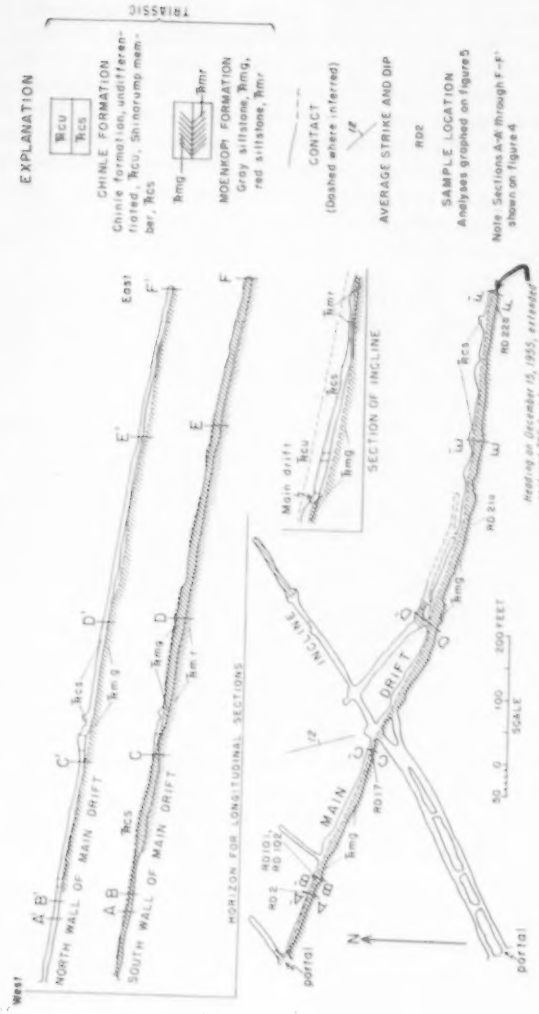

FIG. 3. Plan view and sections of the Rainy Day mine.

Habit of Deposit.—The channel is asymmetric in cross section and curves gently to the north in plan view. The north side of the channel has a gentle slope that resembles the slipoff slopes found on the banks of present day streams; the south side of the channel is steep, locally undercut, and is marked by a series of abrupt slope changes that are probably former stream banks. The ore pod is localized near the top of one of these small banks. The southern edge of the channel, where the Shinarump member of the Chinle formation pinches out, is probably parallel to, and not more than 50 feet south of the ore pod. The sandstone filling the channel is not more than 40 feet thick, and most of this thickness is gained at the expense of the Moenkopi formation (Fig. 3, section of incline), although on the outcrop there appears to be some buildup of sandstone over the central part of the channel. Cross-bed measurements indicate that the sandstone was deposited by a stream that flowed from southeast to northwest.

The Moenkopi in the mine ranges from a mudstone to a siltstone. Quartz, kaolinite, and mica grains, coated with iron oxide, are the main constituents. This rock, normally red, is gray in a 6- to 10-foot zone under the contact with the Shinarump member, but this altered zone is not significantly thicker near the mine than in other places at the contact. A small amount of pyrite occurs in the altered zone, diminishing in quantity toward the contact with unaltered red siltstone. The red siltstone contains no pyrite. The total iron content of the gray rock ranges from 1 to 3 percent and total iron in red siltstone ranges from 3 to 7 percent. The iron removed from the gray rock probably was redeposited in the overlying pyritic sandstone, as pointed out below. Asphaltic material, not soluble in xylol or benzene, is present in the gray siltstone of the Moenkopi formation in the Rainy Day mine, and it may have had some influence on ore deposition.

The sandstone filling the channel is medium to fine grained and contains abundant gray mudstone seams and lenses and carbonaceous material. Quartz, about 1 percent mica, and up to 25 percent kaolinite and altered feldspar are the main rock-forming minerals. The base of the sandstone is locally conglomeratic, especially in the mine, containing pebbles of quartz, quartzite, and chert, and fragments of siltstone and carbonaceous material. Much of the carbonaceous material is partly replaced by pyrite and marcasite. The sediment filling the channel is generally slightly petroliferous, and locally is nearly saturated with a brown to black asphaltic material that dissolves easily in xylol or benzene.

Overlying the channel-filling sandstone with a gradational and intertonguing contact is the Monitor Butte member of the Chinle formation. This unit consists of bentonitic gray to gray-green mudstone and siltstone interbedded with discontinuous lenses of arkosic fine- to medium-grained gray sandstone. This normally gray-green rock is altered to shades of yellow and blue near the north edge of the Rainy Day channel. The alteration probably involves only a change in amount and composition of iron minerals. No unusual radioactivity has been noted in association with this alteration.

The uranium ore is localized near the top of a streambank cut in the silt-

stone of the Moenkopi formation. This pod of ore, illustrated in cross section in Figure 4, is lense shaped measuring about 1½ feet in thickness and 4 feet in width. Locally the host rock is crumpled and sheared, especially at the top of the bank; more commonly it is not noticeably sheared or disturbed. This crumpling is attributed to partial caving during cutting and filling of the channel. The ore pod was localized in the top of the bank at the northwest end of the deposit, but in the southeast end it is more commonly found a foot or two below the top of the bank in essentially undisturbed rock. The ore has been continuous and uniform in grade for its entire mined length of more than 1,800 feet, 1,100 feet of which was mapped and is shown in Figures 3 and 4. Grab samples taken from the central part of the ore pod contain from 1 to 4 percent uranium. The grade decreases gradually away from the center of the pod but drops off abruptly at the contact with the Shinarump member of the Chinle formation. Generally, the Shinarump does not contain minable concentrations of ore, but the operator reports that locally very small patches of sandstone in contact with the ore pod have a high count. Away from the ore pod, the Moenkopi is slightly radioactive along its contact with

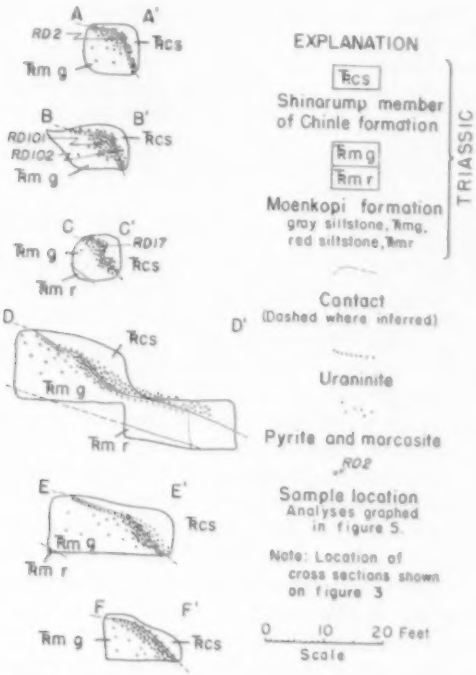

FIG. 4. Geologic cross sections, main drift of Rainy Day mine.

the Shinarump, and this radioactivity diminishes as the distance from the ore body increases.

The ore mineral is isotropic, gray under reflected light, and may be seen only under very high magnification; it is considered to be uraninite. The uraninite fills interstices and microscopic fractures and replaces parts of the siltstone and mudstone of the Moenkopi formation. It is also localized along bedding planes. Chalcopyrite, sphalerite, pyrite, marcasite, and galena, in approximately that order of relative abundance, are associated with the uraninite. No molybdenum minerals were identified in thin or polished sections but ilsemannite can be seen on the exposed surface of rock near ore and spectrographic analyses show as much as 2 percent molybdenum.

Directly overlying the ore, in the Shinarump member, is a fairly continuous zone containing abundant pyrite and marcasite (Figs. 3 and 4). Local concentrations of molybdenum, indicated by development of ilsemannite on mine walls, also occur in this zone. The total iron content in the zone ranges from 3 to 7 percent. This is in marked contrast to the amount of iron occurring in the overlying nonpyritic sandstone, which contains only about 1 percent total iron. The iron in the pyrite-marcasite zone probably was leached out of the gray siltstone that contains 1 to 3 percent iron, or less than half that of the parent red siltstone, but whether by ore solution, or other waters at a time not related to ore deposition, is a matter for conjecture. The zone containing pyrite and marcasite ranges up to 4 feet in thickness and, merging with the pyrite in the gray siltstone of the Moenkopi, forms an imperfect pyritic envelope or halo around the ore pod (Fig. 4, especially section D-D′).

Chemical Changes Due to Uranium Introduction.—Semiquantitative and chemical analyses were made of eight grab samples taken from the Rainy Day channel. A graph of the analyses is presented on Figure 5. These samples show that several elements, notably copper, zinc, nickel, and lead, increase as the grade of uranium increases.

The relative positions of the samples are shown diagrammatically on Figure 5. All of the samples are from the Moenkopi formation; one, RD21a, is unaltered red siltstone; the others are from gray siltstone. Of these, RD2, RD101, RD102, and RD17 are ore samples. RD22b, RM4, and RM3 are only very weakly mineralized. Both RD21a and RD22b are slightly more dolomitic than the other samples. Samples RM3 and RM4 were collected from the prospect at the north edge of the Rainy Day channel (Fig. 2); all other samples are from the Rainy Day mine (Figs. 3 and 4).

The samples are arbitrarily placed in Figure 5, so that uranium increases from left to right. Ytterbium, yttrium, copper, nickel, cobalt, lead, silver, molybdenum, and zinc show a 10-fold or greater increase, from barren rock to uranium ore, similar to that of uranium. The author believes this correspondence indicates that these elements were introduced with, and roughly in proportion to uranium; if this is true they were carried by the ore-forming solutions and were concentrated in the deposit during the ore-forming period. If the slightly greater original dolomite content of RD21a and RD22b is taken into account and the lowest and highest amounts of the elements con-

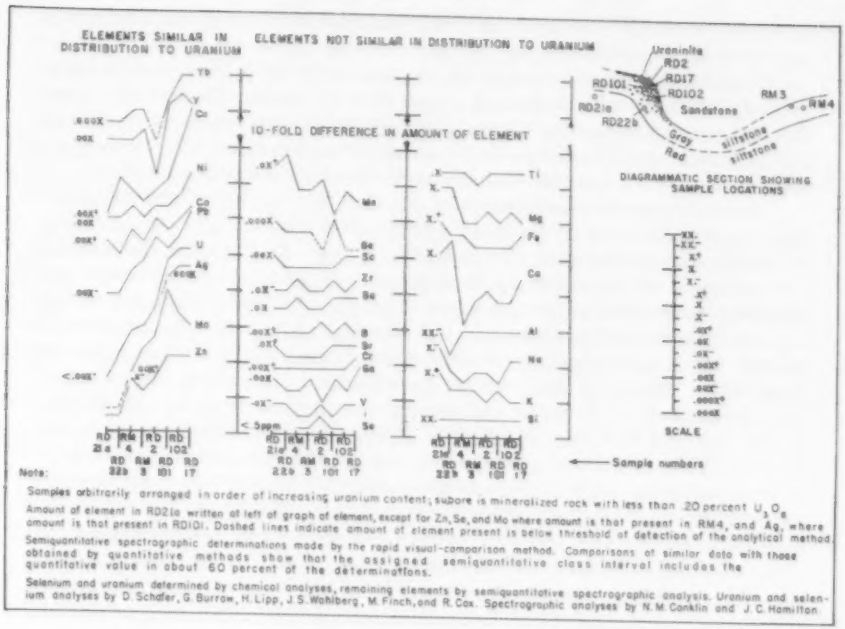
ELEMENTS SIMILAR IN DISTRIBUTION TO URANIUM
ELEMENTS NOT SIMILAR IN DISTRIBUTION TO URANIUM
10-FOLD DIFFERENCE IN AMOUNT OF ELEMENT
Uraninite
RD2
RD17
RD101
RD102
RM 3
RM4
RD21e
Sandstone
RD22b
Gray
Red
Siltstone
Siltstone
DIAGRAMMATIC SECTION SHOWING SAMPLE LOCATIONS
SCALE
Sample numbers
Note:
Samples arbitrarily arranged in order of increasing uranium content; subore is mineralized rock with less than .20 percent U_3O_8
Amount of element in RD21e written at left of graph of element, except for Zn, Se, and Mo where amount is that present in RM4, and Ag, where amount is that present in RD101. Dashed lines indicate amount of element present is below threshold of detection of the analytical method.
Semiquantitative spectrographic determinations made by the rapid visual-comparison method. Comparisons of similar data with those obtained by quantitative methods show that the assigned semiquantitative class interval includes the quantitative value in about 60 percent of the determinations.
Selenium and uranium determined by chemical analyses, remaining elements by semiquantitative spectrographic analysis. Uranium and selenium analyses by D. Schafer, G. Burrow, H. Lipp, J. S. Wahlberg, M. Finch, and R. Cox. Spectrographic analyses by N. M. Conklin and J. C. Hamilton.

FIG. 5. Analyses of ore, subore, and barren rock samples from the Moenkopi formation, Rainy Day mine channel.

sidered, gallium and calcium also show a 10-fold increase corresponding roughly to that of uranium; because of the erratic nature of the gallium curve and the likely fluctuation of amounts of calcium due to ground water removal or deposition of calcite since ore emplacement, their correspondence may not be significant. The chemical trend of samples RM3 and RM4 from the north side of the channel closely follow the chemical trend of the samples from the Rainy Day mine. The location of the samples suggests that the ore solutions which formed the Rainy Day deposit probably traversed the entire channel sandstone deposit, but formed minable concentrations of uranium only at the southern edge in the Moenkopi formation.

Analyses of unmineralized sandstone and uranium-ore sandstone samples from the Shinarump and Moss Back members of the Chinle formation, collected from the entire Colorado Plateau, show that samples from ore deposits have a 10-fold or greater increase, from barren rock to uranium ore, in vanadium, cobalt, nickel, copper, zinc, yttrium, molybdenum, and lead (William L. Newman, oral communication, 1957). Thus, except for the lack of an increase in vanadium and an increase in silver and ytterbium, the ore at the Rainy Day mine from the Moenkopi formation has nearly the same suite of

added or "extrinsic" elements as ore bodies in sandstone of the Shinarump and Moss Back members of the Chinle formation.

These samples point up an ore guide that has already been used by prospectors, especially with regard to copper staining in the Circle Cliffs area; that is—channel sandstone showing enrichment in the elements associated with uranium are more favorable for prospecting than sandstone showing no enrichment at all, no matter how favorable the channel fill looks otherwise.

Possible Structural Localization of the Ore Body.—As pointed out above the deposit is localized on the eastern flank of the Circle Cliffs anticline, near where the rate of change of dip increases rapidly. In the mine the localization of ore is not controlled by through-going large fractures or joints, and probably is controlled only to a minor extent by fractures caused by slumping during cutting of the channel. The structure surface near the mine is not smooth, but is quite irregular, having several bumps and hollows. Several maps which eliminated the regional structure and isolated the minor structures were constructed, in line with general principles outlined by Dobrin (1), Griffin (4), and Nettleton (11). The deposit is located almost on the center of a saddle formed by the intersection of a northwest-trending low and a northeast-trending high. The structural relief above and below the generalized regional structural surface was on the order of 200 to 300 feet. The correlation between the minor structures and the deposit did not suggest an obvious control. The ore body does not appear to be controlled by the present regional structure. It is almost impossible to say whether or not an earlier structure or an early stage of the present regional structure, now masked, is responsible for the localization of the ore body.

CONCLUSIONS

The Rainy Day deposit is localized in siltstone to mudstone in contrast to most other minable deposits in Triassic rocks which are in much more permeable rock—generally sandstone. In addition, the siltstone has only small amounts of asphaltic material, whereas, the sandstone has moderate to abundant amounts of asphaltic and charcoally material. The cause of the peculiar localization is unknown. It seems most likely that the sandstone filling the channel provided the main conduit for the ore solutions since the mudstone above and the siltstone below the sandstone are much less permeable than the sandstone deposit in the channel. The chemical similarity of the samples from the north edge of the channel to those from the Rainy Day deposit supports this contention. Yet, essentially none of the sandstone in the channel deposit, nor any of the abundant carbonaceous or asphaltic material in the sandstone is mineralized with uranium.

Ore textures indicate the ore minerals are later in age than the host rock; it is probable that this deposit is approximately the same age as other Colorado Plateau ores which, according to Stieff and others (14), are 71 to 82 million years old, based on Pb^{206}/U^{238} and Pb^{207}/U^{235} ratios. Thus the deposit was probably emplaced during the latter part of the Cretaceous period. The

folding of the Circle Cliffs structure has involved Upper Cretaceous rocks, and the Wasatch formation of early Eocene age truncates the structure to the north and west. The regional structure, therefore, probably ranges from Late Cretaceous to early Eocene in age. Hence, ore deposition may have preceded or occurred approximately at the same time as the main structural deformation. The flow of ore solutions may have been controlled by an early development of the regional structure, later masked by more vigorous folding; efforts to isolate such an early structure proved fruitless.

Possible sources of ore solutions, ably discussed in considerable detail by Gruner and others (7), Gruner (6), Fischer (2), and McKelvey and others (10), seem limited to ground water or hydrothermal sources or perhaps a combination of the two. The intense alteration of the Chinle formation at the northern edge of the channel and the mineral assemblage in the deposit seem to favor a hydrothermal source, yet the bleaching and even the typical "hydrothermal minerals," chalcopyrite, galena, and sphalerite, may have originated from more or less cool ground (?) waters. Chemical evidence does not eliminate either source. The direction of solution transport, which might be helpful in ascertaining source directions, is not at all clear from the structural picture, nor are techniques for determining the direction of ore solution flow (5) applicable, mainly because of the small size of the deposit.

Semiquantitative spectrographic analyses of rock directly underlying a channel in the Circle Cliffs area would be valuable in locating places higher than normal in copper, silver, molybdenum, and zinc content. These channels, on evidence submitted here, are more favorable places for prospecting than places where there is no enrichment of these critical elements. This technique might also apply in other regions of the Colorado Plateau.

U. S. Geological Survey,
Tucson, Ariz.,
Aug. 6, 1958

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AN APPLICATION OF STATISTICAL ANALYSIS TO EXPLORATION FOR URANIUM ON THE COLORADO PLATEAU

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ABSTRACT

The literature on the Colorado Plateau uranium-vanadium deposits before 1944 includes many geologic factors that could have influenced the deposition of the uranium and vanadium ore-minerals. Maps are drawn showing the relationships between these influencing geologic factors and the ore deposits, and the data on these maps transferred, using a grid system, to record sheets. These data are then ranked and analyzed using Spearman's coefficient of rank correlation. The units of the subdivided geologic factors that gave significantly positive correlations with the productivity of the deposits are combined graphically to show the most favorable areas. Deposits that were discovered after 1944 are compared to the outlined favorable areas to show the validity of this type of analysis as a mineral exploration tool.

A little less than 78 percent of the uranium-vanadium deposits on the Colorado Plateau that were discovered in the lower part of the Morrison formation after the analysis period (pre-1944) were inside of the areas outlined by the analysis as favorable. This suggests strongly that the statistical analysis can be used as a mineral exploration tool to outline areas favorable for ore deposits.

INTRODUCTION

STATISTICAL analysis, although proven useful in many fields, has not been seriously applied to mineral exploration and exploitation. It was used at Riddle, Oregon, and on the Colorado Plateau in ore reserves studies, but the author knows of only one attempt to apply statistical analysis to determine the regional distribution of mineral deposits. Lampietti (12) statistically analyzed the deposits within a 200-mile radius of Boulder Dam, Arizona. By correlating the distribution of the deposits with Burnham's (1) trace element data he outlined favorable areas for future exploration. However, his favorable areas have not been explored and the value of his work has not been proven.

The usefulness of statistical analysis in mineral exploration can be tested by analyzing a mineralized region that has had two or more production periods in one or more associated metals. One or more of the early periods can be analyzed and the results used to outline areas in which more deposits can be expected. The outlined areas can then be compared with the distribution of the deposits discovered after the analysis period to check the validity of the statistical predictions.

This paper illustrates the value of statistical analysis in mineral exploration

by analyzing the uranium-vanadium deposits on the Colorado Plateau. There is enough information available to analyze the uranium-vanadium deposits as of 1944 (the end of the second period of activity) and to compare the statistical predictions resulting from the analysis with the present (third) production period.

In this paper, the methods of cataloguing and analyzing the geologic data are stressed rather than the geology of the deposits and the hypotheses concerning their genesis.

The area studied in this analysis is shown in Figure 1.

GEOLOGIC FACTORS

In any statistical study all the available information on the subject should be collected and compiled in such a manner as to make it suitable for analyzing. Here, all the available literature on sedimentary type ore deposits and in particular uranium-vanadium deposits on the Colorado Plateau before 1944 were scanned and the pertinant data compiled. These data included estimates of the total production and reserves of the Morrison formation uranium-vanadium deposits in 1944, the geology of the deposits, and the hypotheses on the origin and emplacement of the ore minerals.

The majority of the known uranium-vanadium deposits on the Colorado Plateau in 1944 were in the Salt Wash member of the Morrison formation. A few deposits, however, were in an interfingering area of the Salt Wash and Recapture members of the Morrison formation near the Four Corners area of Colorado, Utah, Arizona, and New Mexico. Therefore, this analysis includes only the Salt Wash and Recapture members in the lower part of the Morrison formation.

The literature prior to 1944 contains many descriptions of the geologic factors that could have influenced the location of the uranium-vanadium orebodies. Some of these factors are the presence of carbonaceous material (9), lithology of the host sandstone (8), the lensy character of the host sandstone (2), the thickness of the host sandstone layers (8), presence of structural features (3), and the origin of the uranium and the vanadium.

Before 1944, three major hypotheses on the origin of the ore (hydrothermal, syngenetic, and ground-water concentration) had been proposed by students of the problem. The hydrothermal hypothesis was mentioned by several authors (3, 7, 9, 13), but it was immediately discredited by them because of the lack of uranium and vanadium in the nearby igneous intrusives and the lack of the customarily expected hydrothermal accessory minerals in the deposits. The non-uniform distribution of the deposits relative to the igneous intrusions was cited also as evidence against the hydrothermal hypotheses (4). Up to 1944, the syngenetic hypothesis was favored by many geologists as the best explanation for the origin of the uranium and vanadium. The proponents of this hypothesis (4, 7, 9) argued that the ore elements were originally contained in the Morrison source area rocks or veins and were deposited with the sediments as placer minerals, as organic extractions, or as inorganic precipitates. The hypothesis that the uranium and vanadium

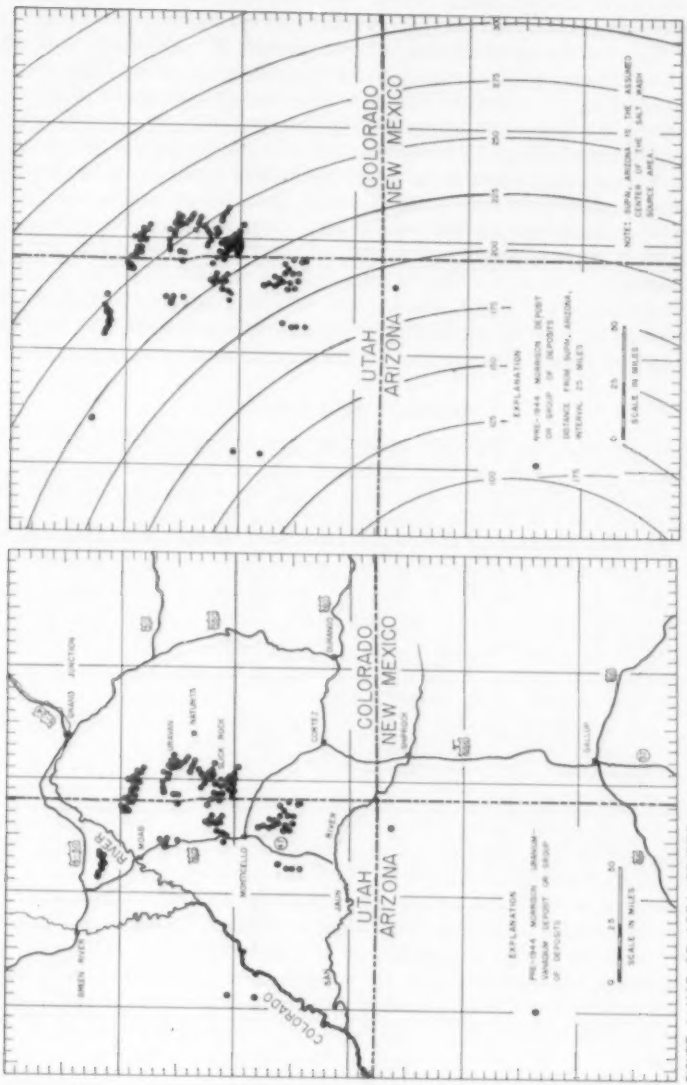

FIGURE 1 - MAP OF AREA STUDIED

FIGURE 2 - MAP SHOWING THE RELATION OF THE MORRISON DEPOSITS TO THE SOURCE AREA OF THE SALT WASH SEDIMENTS.

were concentrated by ground water action from the dispersed sources within the stratigraphic column was proposed to explain some of the apparent inconsistencies involved in the other hypotheses. Two authors (3, 13) favored the idea that the ore elements were deposited with the sediments and later dissolved and transported to the sites of deposition by ground water, and another (11) suggested that the elements could have been leached from overlying volcanic ash layers and transported to the sandstones by ground water.

This brief mentioning of items connected with the geology of the deposits is merely to enumerate some of the many factors that could affect the location of the uranium-vanadium orebodies. Some of these factors can be considered on a regional basis and studied on the plan proposed here, but others are too local for a regional study and would have to be examined by a different type of analysis. All of the factors on which there were data that could be plotted were studied in this analysis. The main objective was to determine what factors controlled the regional distribution of the ore bodies, by applying the methods of statistical analysis.

PREPARATION OF DATA

One of the major problems in preparing data for statistical analysis is to design the problem or experiment in such a way as to eliminate bias on the part of the person making the analysis. There are many ways in which to do this, and as many of them as possible were used in this study.

The first bias eliminating techniques were used in the construction of the maps. A map of the Colorado Plateau region was chosen with a scale such that all of the deposits known in 1944 fell well within an arbitrarily selected 13 by 16 inch rectangle. The rectangle was drawn on a piece of tracing paper and arbitrarily laid over the map of the Colorado Plateau region with the long side oriented north-south. A tracing was made of the map and the Morrison formation uranium-vanadium deposits known in 1944 were plotted on the tracing. An arbitrarily selected 5-by-5 mile grid was constructed within the rectangle by starting at the northeast corner and working south and west. This grid system is another bias eliminating technique. For clarity only the tenth grid lines (50th mile) were drawn on the map and the others were located by tick marks along the border. Duplicates of this tracing were made and used as base maps for plotting the geologic factors that could have controlled the deposition of the uranium and vanadium minerals.

The data on several of the maps are after Craig et al. (5) who studied the Morrison and related formations from 1947 to 1951. The use of his data for this 1944 analysis period is justified on the basis that the outcrops of the Morrison formation were available for measurement long before the analysis period and anyone could have measured them. Had the author actually made the study in 1944 his first step would have been to collect data on the Morrison formation.

The maps used here are described briefly below.

The map showing the distance travelled by the Salt Wash sediments (Fig. 2) serves several purposes. It gives a crude approximation of the character of the Salt Wash relative to the source area, and it can be used to test the

syngenetic hypothesis by comparing the deposits with the distance from the source area. The center of the source area is assumed to be Supai, Arizona; this assumption is based on data from Craig et al. (5) and Stokes (14).

Figure 3, the map of the igneous intrusions, can be used to test the hypothesis that the deposits are related to igneous activity by studying the deposit-igneous intrusion distances.

The Brushy Basin member of the Morrison formation (Fig. 4) can be considered as a possible source of the uranium, and the thickness of this member might have a relation to the intensity of mineralization in a particular area.

The isopachous and isolith maps of the Recapture member, Salt Wash member, and stream deposits in the lower part of the Morrison formation (Figs. 5 through 11), indicate the physical characteristics of the favorable sandstone. They are used to determine what conditions in the host rocks seem to influence the deposition of the ore minerals.

Some factors such as the presence of carbonaceous material and the proximity of structural features cannot be analyzed on maps of this scale.

METHOD OF ANALYSIS

There are several methods that could be used to analyze the collected data. Therefore, the data were examined to determine what method for associating the predictor variables (the geologic factors) with the deposits would give the most usable results for outlining favorable areas.

The usual method for handling problems of this kind is by multiple regression analysis, but the large number of variables, together with the fact that some of them are qualitative, make this method impractical. It was decided to rank the data and deal with the ranks, since it was believed that only large changes in the predictor variables would have noticeable regional effects on the production levels. The production of the deposits (Fig. 12) was chosen as the base criterion for determining which variables should be used to delineate favorable areas, and Spearman's coefficient of rank correlation was chosen from among the measures of association applicable to ranked data (10).

The geologic and lithologic factors that could have influenced the deposition of the uranium and the vanadium minerals were then sub-divided into four levels for the initial analysis. The levels for the different factors are given below.

Distance from Supai, Arizona in miles	Level
0–150	0
150–200	1
200–250	2
More than 250	3

Distance from nearest intrusion in miles	Level
0–30	1
30–60	2
60–90	3
More than 90	4

Thickness of the Brushy Basin in feet	Level
0	0
0–150	1
150–300	2
More than 300	3

Thickness of the Salt Wash in feet	Level
0	0
0–200	1
200–400	2
More than 400	3

Thickness of the lower part of the Morrison formation in feet	Level
0	0
0–200	1
200–400	2
More than 400	3

Thickness of stream deposits in feet	Level
0	0
0–150	1
150–300	2
More than 300	3

Ratio of stream deposits to floodplain deposits	Level
0	0
0–1.5	1
1.5–3.0	2
More than 3.0	3

Percent mean deviation of stream deposit thickness	Level
0	0
0–10	1
10–20	2
More than 20	3

Log standard deviation of grain size	Level
0–1.0	0
1.0–1.1	1
1.1–1.2	2
More than 1.2	3

Percent of stream deposits in the lower part of the Morrison formation	Level
0	0
0–30	1
30–60	2
More than 60	3

Production in tons	Level
0	0
0–100	1
100–1,000	2
1,000–10,000	3
More than 10,000	4

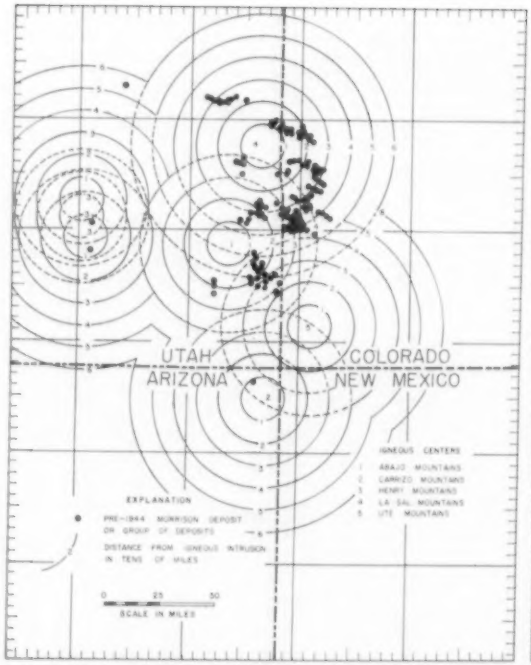

FIGURE 3—MAP SHOWING THE RELATION OF THE MORRISON DEPOSITS TO THE CENTERS OF IGNEOUS INTRUSION.

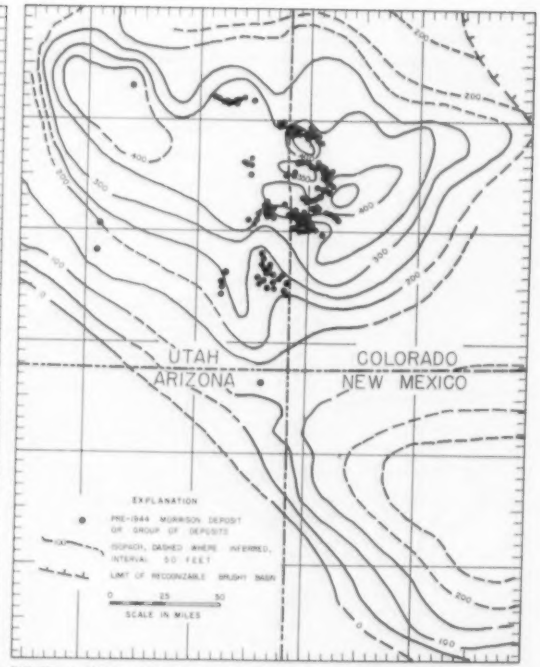

FIGURE 4—MAP SHOWING THE RELATION OF THE MORRISON DEPOSITS TO THE THICKNESS OF THE BRUSHY BASIN MEMBER. (ISOPACH AFTER CRAIG, ET. AL. U.S.G.S. TEI 180, P.50, 1951)

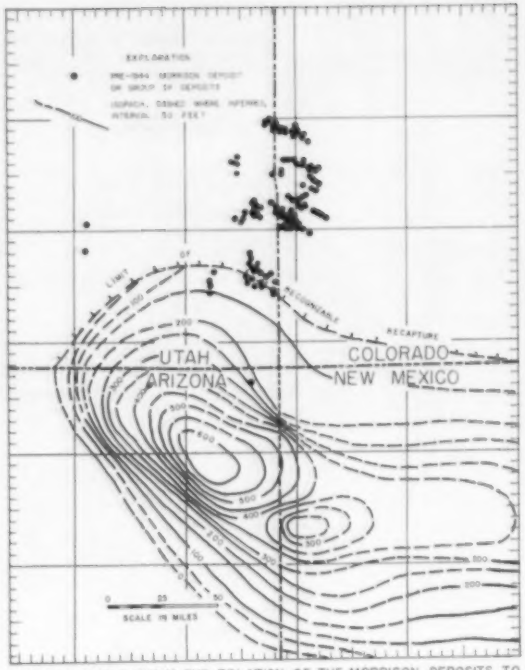

FIGURE 5-MAP SHOWING THE RELATION OF THE MORRISON DEPOSITS TO THE THICKNESS OF THE RECAPTURE MEMBER. (ISOPACH AFTER CRAIG, ET. AL. U.S.G.S. TEI 180, P.26, 1951)

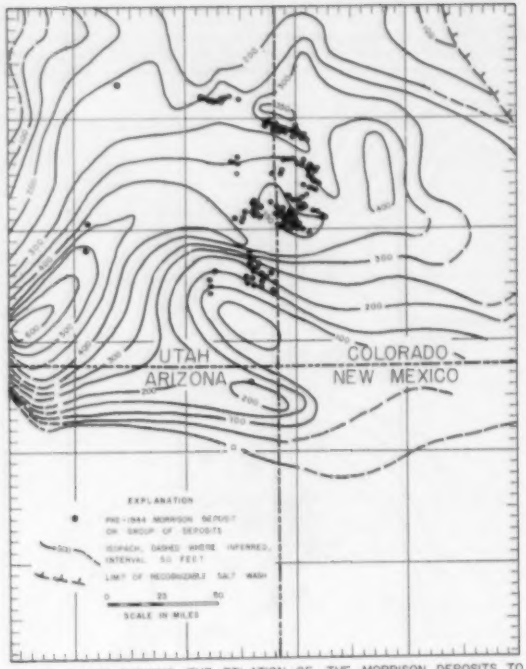

FIGURE 6-MAP SHOWING THE RELATION OF THE MORRISON DEPOSITS TO THE THICKNESS OF THE SALT WASH MEMBER. (ISOPACH AFTER CRAIG, ET AL. U.S.G.S. TEI 180, P. 21, 1951)

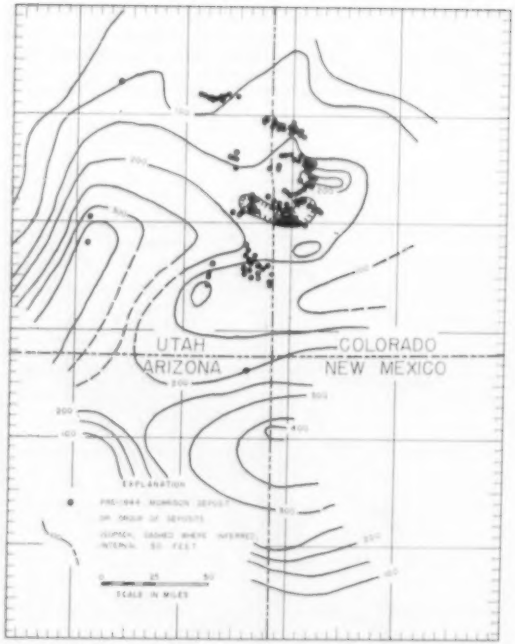

FIGURE 7—MAP SHOWING THE RELATION OF THE MORRISON DEPOSITS TO THE THICKNESS OF THE STREAM DEPOSITS IN THE LOWER PART OF THE MORRISON FORMATION. (ISOPACH AFTER CRAIG, ET AL. U.S.G.S. TEI 180, P.29, 1951)

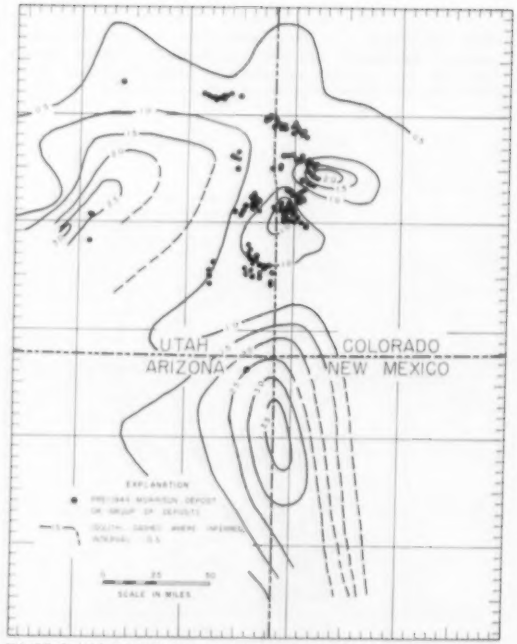

FIGURE 8—MAP COMPARING THE MORRISON DEPOSITS TO THE RATIO OF STREAM DEPOSIT THICKNESS TO FLOODPLAIN DEPOSIT THICKNESS IN THE LOWER PART OF THE MORRISON FORMATION. (ISOLITH MAP AFTER CRAIG, ET AL. U.S.G.S. TEI 180, P.31, 1951)

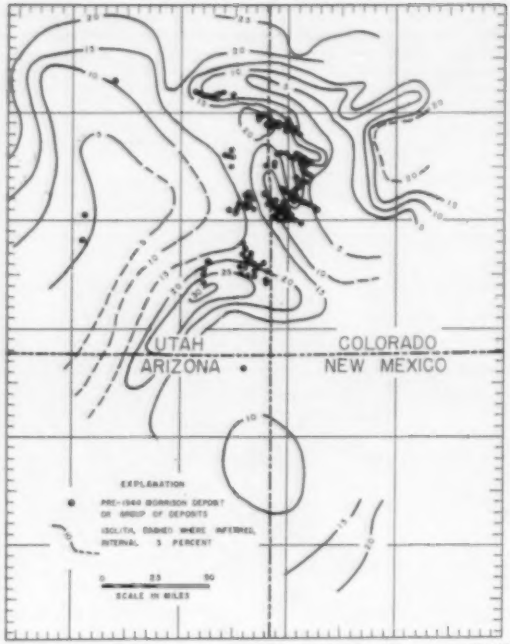

FIGURE 9-MAP COMPARING THE MORRISON DEPOSITS TO THE PERCENT MEAN DEVIATION OF STREAM DEPOSIT THICKNESS IN THE LOWER PART OF THE MORRISON FORMATION (ISOLITH MAP AFTER CRAIG, ET AL. U.S.G.S. TEI 180, P 32, 1951)

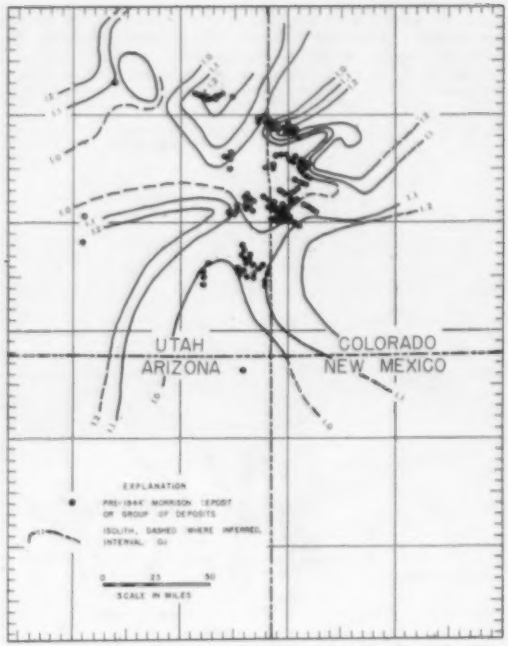

FIGURE 10-MAP COMPARING THE MORRISON DEPOSITS TO THE LOGARITHMIC STANDARD DEVIATION OF GRAIN-SIZE DISTRIBUTION IN THE SANDSTONES OF THE SALT WASH MEMBER. (ISOLITH MAP AFTER CRAIG, ET AL. U.S.G.S. TEI 180, P 39, 1951)

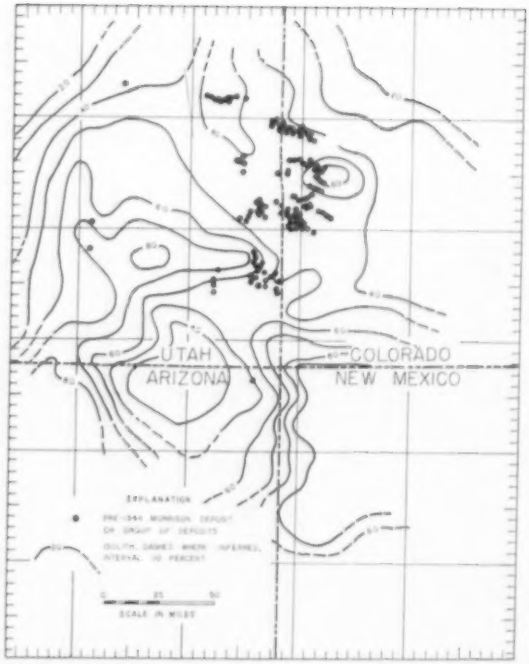

FIGURE 11-MAP SHOWING THE RELATION OF THE MORRISON DEPOSITS TO THE PERCENTAGE OF STREAM DEPOSITS IN THE LOWER PART OF THE MORRISON FORMATION.

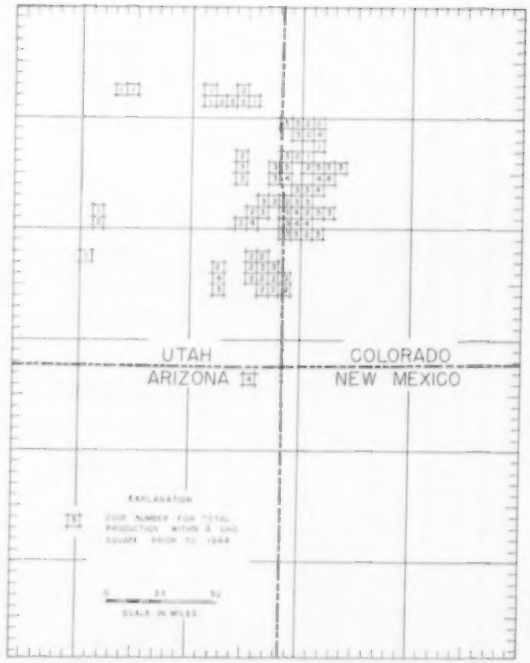

FIGURE 12-MAP OF THE PRE-1944 PRODUCTION LEVELS FOR THE MORRISON FORMATION URANIUM-VANADIUM DEPOSITS.

After the above decisions were made came the process of assembling all of the data into a statistically analyzable form. The first step in this compilation was the transferring of the production and the factor level data in a given grid square on each of the eleven maps to a master record sheet grid. However, rules to govern the procedures of observing and recording the data were set down before the counting began. The rules are briefly stated below.

In making observations on the production, the sum of the productions of the deposits in a grid square was taken and the level of the total recorded. In making an observation on the isopachous and isolith maps, the level was recorded for the thickness or number range represented by the largest area

TABLE 1

GEOLOGIC FACTOR LEVEL PERCENTAGES FOR DIFFERENT PRODUCTION LEVELS

Production	Distance from Sujai, Arizona	Distance from igneous intrusion	Thickness of Brushy Basin	Thickness of Salt Wash	Thickness of lower part of the Morrison	Thickness of channel deposit	Ratio of stream to floodplain	% mean deviation stream deposit thickness	Log mean deviation grain size	% stream deposit in lower part of the Morrison	Level
4	—	—	—	—	—	—	—	—	—	—	4
	33.3	—	83.4	—	—	—	—	8.3	8.3	16.6	3
	50.0	41.7	8.3	83.4	100	66.7	25.0	33.3	—	83.4	2
	16.7	58.3	8.3	16.6	—	33.3	75.0	58.4	41.6	—	1
	—	—	—	—	—	—	—	—	50.0	—	0
3	—	—	—	—	—	—	—	—	—	—	4
	3.7	—	88.9	—	—	—	—	3.7	11.1	7.4	3
	92.6	74.1	11.1	92.6	100	59.3	—	74.1	7.4	92.6	2
	3.7	25.9	—	7.4	—	40.7	100	22.2	25.9	—	1
	—	—	—	—	—	—	—	—	55.6	—	0
2	—	—	—	—	—	—	—	—	—	—	4
	7.4	—	51.8	7.4	7.4	3.7	—	22.2	7.4	22.2	3
	81.5	7.4	48.2	66.6	81.5	37.0	7.4	59.3	14.8	77.8	2
	11.1	92.6	—	26.0	11.1	59.3	92.6	18.5	55.6	—	1
	—	—	—	—	—	—	—	—	22.2	—	0
1	—	—	—	—	—	—	—	—	—	—	4
	11.1	—	66.7	22.2	22.2	11.1	—	—	—	22.2	3
	66.7	44.5	33.3	77.8	77.8	22.2	11.1	55.5	37.5	77.8	2
	11.1	55.5	—	—	—	66.7	88.8	44.5	37.5	—	1
	11.1	—	—	—	—	—	—	—	25.0	—	0
0	—	5.7	—	—	—	—	—	—	—	—	4
	31.8	18.0	29.6	5.9	17.4	9.2	4.9	10.5	23.4	19.8	3
	31.0	37.0	39.0	54.4	66.2	29.6	18.7	55.4	21.0	69.0	2
	24.4	39.2	16.7	28.1	16.4	61.2	76.5	34.1	23.8	11.2	1
	12.8	—	14.7	11.6	—	—	—	—	31.8	—	0

in the grid square. If two or more isopach lines crossed a square then the weighted average thickness was taken and the level for the average recorded.

In general the counting was straightforward, but occasionally a circle for a group of deposits fell on a grid line or an isopach or isolith line bisected the area of a square. These problems were solved as follows. If a deposit circle fell on a grid line or on the intersection of two grid lines, the production within the circle was divided in proportion to the area of the circle on each side of the line. The decision on which observation to take where an isopach or isolith line bisected the area of a square was made by tossing a coin.

After the counting was completed the data were summarized in a table showing the percentage of the factor levels in each production level (see Table 1).

Before Spearman's coefficient of rank correlation could be calculated for the factor levels, the collected data had to be ranked. The ranking was assisted by the construction of a 2-by-2 table for each of the factors from Table 1. The 2-by-2 table is used to show a measurement or observation that is related to given levels of two variables. The highest percentage number under a factor level was given a rank of 5 and the lowest percentage number under the same factor level was given a rank of 1. The 2-by-2 table for the thickness of stream deposit factor (Fig. 7) is given below.

Production ranking	Factor levels (in percents)				Total percent
	0	1	2	3	
5	—	33.3 [1]	66.7 [5]	— [1, 2]	100
4	—	40.7 [2]	59.3 [4]	— [2, 1]	100
3	—	59.3 [3]	37.0 [3]	3.7 [3]	100
2	—	66.7 [5]	22.2 [1]	11.1 [5]	100
1	—	61.2 [4]	29.6 [2]	9.2 [4]	100
Spearman's coefficient	—	−0.90	0.90	−0.80 −0.90	

The numbers in brackets show the ranking for each level.

The next step was to measure the association between the ranks of each level and the ranks of production by the use of Spearman's coefficient. In the case of tied ranks, the more usual method is to use the mean of the tied ranks, i.e., 1.5 in the case of the top two boxes of level 3. However, since there are only five ranks, all possible cases were considered and all coefficients were computed.

Spearman's coefficient of rank correlation is given by (10)

$$\rho = 1 - \frac{6 \sum_{i=1}^{n} d_i^2}{n(n^2 - 1)}.$$

Where Σd_i^2 is the sum of the squares of the differences of adjacent members of two rankings, and n is the number of members in each ranking.

Spearman's ρ is close to 1.0 if there is a nearly perfect positive association between the rankings, and it is close to -1.0 if there is a nearly perfect disassociation between the rankings. If there is no correlation between the rankings, then ρ is near 0.0. In this study there are only five members in each ranking (the number of production levels), so a coefficient has to be 0.90 to 1.00 or -0.90 to -1.00 before it can be called significant.

Naturally, only the factors that give significant correlations can be used to outline favorable areas.

The calculation of ρ for level 1 of the thickness of stream deposit factor is given below as an example of the procedure.

Production ranking	5	4	3	2	1
Level 1 ranking	1	2	3	5	4
d_i	4	2	0	−3	−3
d_i^2	16	4	0	9	9

$\Sigma d_i^2 = 38$

$$\rho = 1.00 - \frac{6(38)}{5(25 - 1)} = 1.00 - 1.90 = \textit{-0.90}$$

The italicized number was recorded at the bottom of the 2-by-2 table so it could be easily compared with the coefficients for levels 2 and 3. In this case the factor level No. 2 seems to have a favorable influence on the location of the deposits as it shows a significant positive correlation with the production.

It is evident that the levels are not independent since in any horizontal row the sum of the percents in the 2-by-2 table must equal 100. However, in this problem, if there is only one significant positive correlation and it is surrounded by significantly negative correlations; then the arbitrarily chosen limits of the level that has the positive correlations would seem to have been properly selected. Then these limits having the significantly positive correlation can be used to outline the favorable areas. If the level with the positive correlation were not flanked by levels with significantly discordant correlations, then the limits of the significantly concordant level should be changed until the best limits are determined. It should be pointed out that 0.90 and -0.90 are just barely significant so there may be some slight changes in the limits even when a significantly positive level of 0.90 is flanked by significantly negative levels of -0.90.

All factor levels and some combined factor levels were analyzed in the same way. The Spearman's coefficient for all of the analyzed factor levels are recorded in Table 2.

After completing this analysis, the factors that seem to be favorable predictor variables for ore deposits were re-examined using finer level divisions

TABLE 2

SPEARMAN'S COEFFICIENT OF RANK CORRELATION FOR FACTOR LEVELS THAT WERE ANALYZED (1.00 AND 0.90 INDICATE SIGNIFICANT CONCORDANCES)

Factors	Levels						
	0	1	2	3	0–1	1–2	2–3
Distance from Supai	—	0.30	0.40	0	—	—	0.70
Distance from igneous intrusion	—	0.20	0.30	—	—	—	—
Thickness of Brushy Basin	—	—	−0.70	0.80	—	—	—
Thickness of stream deposits	—	−0.90	*0.90*	−0.80 −0.90	—	*0.90* 0.80	*0.90*
Thickness of Salt Wash	—	−0.30	0.80	−0.70 −0.60	—	*0.90* 0.80	0.30
Thickness of lower part of Morrison	—	0	*0.90* *1.00*	−0.90 −0.80	—	0.80 *0.90*	—
Ratio stream deposits to flood-plain deposits	—	0	0	—	—	—	—
% mean deviation stream deposit thickness	—	0.20	0	−0.10	—	0.10	−0.10
Log mean deviation grain size	0.50	0.50	−0.90	−0.10	*1.00*	−0.60	−1.00
% stream deposit in lower part of the Morrison	—	—	*0.90* 0.80	−0.60 −0.50	—	0.50 0.60	—

to be sure that the boundaries were properly chosen. The methods used were identical to the ones described above except that the geologic factors were divided into 6 to 13 levels. All of these factor levels and some of the combined levels were analyzed using Spearman's coefficient of rank correlation. The coefficients were recorded in tables similar to Table 2. The limits that seemed to give the best correlations were picked from the tables. These limits are given below with the factors.

Factors	Decoded levels
Thickness of stream deposits	100 to 400 feet
Thickness of Salt Wash	50 to 400 feet
Thickness of lower part of the Morrison	More than 250 feet
Log mean deviation grain size	Less than 1.1
Percent stream deposit in lower part of the Morrison	40% to 60%

DETERMINATION OF FAVORABLE AREAS

As it appears that several factors controlled the deposition of the uranium-vanadium minerals, the combination of these should give the best conditions for ore-deposit formation.

These factors were combined graphically to determine the most favorable areas for more uranium-vanadium deposits. The portions of the favorable

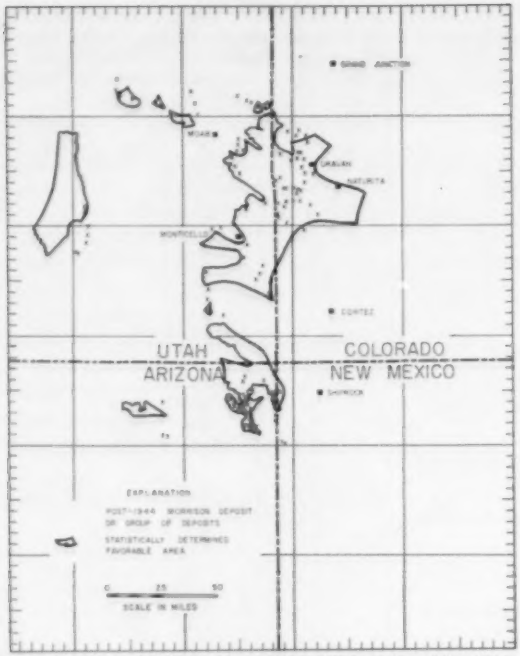

FIGURE 13—MAP COMPARING THE URANIUM-VANADIUM DEPOSITS FOUND IN THE LOWER PART OF THE MORRISON FORMATION AFTER 1944 TO THE STATISTICALLY DETERMINED FAVORABLE AREAS.

areas in which the Morrison formation has been eroded were deleted and the remaining favorable areas were outlined in Figure 13.

There is a possibility that deposits will be found in the fringe area (because of local conditions), but most of the post-1944 deposits should fall inside the most favorable areas.

TESTING THE ACCURACY OF THE PREDICTION

Figure 13 also shows graphically the accuracy of the author's statistical prediction. The "x's" show the location of post-1944 Morrison formation uranium-vanadium deposits. The locations of these deposits were determined from Finch's map (6) after correcting for the pre-1944 deposits.

The salient facts are:

1. A little less than 78 percent of the deposits discovered after 1944 are inside the area.

2. No new areas of mineralization have been found since 1944 in the lower part of the Morrison formation outside of the outlined favorable area.

3. Most of the deposits that have been found outside of the favorable area since 1944 are in areas that were known to contain uranium-vanadium deposits in 1944.

4. Many deposits have been found since 1944 in the outlined area south of the Northeastern corner of Arizona.

5. Up to 1944, approximately 95 percent of the uranium-vanadium ore produced on the Colorado Plateau came from inside the outlined favorable areas. Detail production data on the productions after 1944 are not available for comparison, but the author expects that a similar percentage of the post 1944 production from the lower part of the Morrison formation came from inside of the outlined area.

CONCLUSIONS

1. Statistical analysis can be used on the Colorado Plateau to outline favorable areas for further exploration. The author feels that a similar approach can be used to outline favorable exploration targets in other areas.

2. Local conditions that cannot be expressed as part of the regional pattern may give deposits outside the outlined favorable areas.

3. The results of this analysis have eliminated large areas of the Morrison formation as unfavorable.

4. The position of ore deposits appears to be controlled by physical characteristics of the Salt Wash and Recapture members of the Morrison formation.

5. No large areas of favorable ground in the lower part of the Morrison formation have been overlooked in the recent uranium exploratory activities.

6. The areas immediately east of Monticello, Utah and south of Naturita, Colorado appear to be favorable. However, the drilling depth in parts of these areas is too great for an economically feasible exploration program based on the results of this analysis exclusively.

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July 11, 1958

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PLATINUM DEPOSITS OF ETHIOPIA

E. W. MOLLY

ABSTRACT

The platinum deposit of Yubdo (Wallaga Province), in western Ethiopia, is of the same type of those of the Urals. It shows a dunitic core surrounded concentrically by pyroxenites and by gabbros. This arrangement of increasing basic character toward the center is typical of the Urals deposits.

The Yubdo deposit, however, shows one particular feature, the capping of the dunites by "birbirites" which consist essentially of secondary silica and limonite, and are derived from the dunites through alteration and concentration processes.

The primary mineralization is not mined because of the very low platinum content of the dunites and birbirites. The capping eluvium has been worked for the past thirty years in a fairly primitive fashion, and it is largely exhausted. On the other hand, the alluvium of the present and of former beds of the Birbir river, occurring downstream from the deposit, and which have been left intact because of their position below the hydrostatic level, seems to offer fairly notable possibilities.

INTRODUCTION

Platinum was discovered at Yubdo, in Western Ethiopia, in 1924 by two Italian gold prospectors, A. Prasso and A. Zappa. The deposit and the neighbouring areas, including the valley of the Birbir river as well, had long been worked for gold by the local people, but platinum was unknown and rejected with the tailings.

I organized for a French group, between 1926 and 1928, the first platinum workings. Thirty years later, through a fortunate coincidence, an assignment for an American company brought me back to the same area. I am grateful to Newmont Mining Corporation for the authorization to publish the following notes on that little known region.

The Yubdo area lies in the province of Wallaga, on the right bank of the Birbir river, at an average elevation of 1,600 m, at latitude 8°56′ N and longitude 35°26′ E.

The country is rolling and consists of a plateau area dissected by the Birbir and its tributaries, with the top of the hills generally bare. The Birbir, a tributary of the upper Nile, has a permanent but greatly varying flow according to the season, with an approximate average of 50 m^3 sec. The area, which is healthy and with a fertile soil, is fairly densely populated, mostly by Gallas people who are peaceful farmers, but also skilful with a gold pan when the opportunity arises.

The nearest town is Dembidolo, linked to Yubdo by an 80 mile road and serviced daily by Ethiopian Airlines. During the dry season, Yubdo is

accessible from Addis-Abeba by a 348-mile road. Formerly the trip by caravan lasted 3 weeks, but it is now made in 2–3 days from the capital.

GENERAL GEOLOGY

Since W. T. Blanford who, in 1869, laid down the base of Ethiopian geology (1), numerous authors from various countries but with a predominance of Italians (Stefanini-Dainelli-Usoni (2)), have written on the subject, dealing with either the whole of Ethiopia or some particular regions. They could not all be mentioned in this brief article. Complete bibliographies will be found in specialized publications.

One can distinguish in Ethiopia five main series of formations:

a—Crystalline rocks forming the basement.
b—Subhorizontal sedimentary formations, ranging from Triassic to Cretaceous, which hide the basement in the North and in the East of the country, but are absent in the West and the Southwest.
c—Volcanic trap rocks (of Upper Cretaceous and lower Tertiary) which overlie the sedimentary series in the North and East, but are in direct contact with the basement rocks in the West and the Southwest.
d—Volcanic rocks later than the formation of the Ethiopian Rift Valley.
e—Tertiary and Recent sediments.

The crystalline rocks of the Ethiopian shield consist of gneisses, mica-schists and other metamorphic schists (chloritic, sericitic, feldspathic, amphipolitic, etc.), crystalline limestone, conglomerates, as well as igneous acid and basic rocks (granites, granodiorites, diorites, gabbros, pyroxenites and peridotites) and dikes or lenses of aplites and pegmatites.

The structural trend of the basement rocks is generally from NE to NW, with steep dips to the East or to the West, but erratic trends and low dips are sometimes observed.

There is little known about the relationship of those various formations and most authors observe that it is not possible to distinguish a continuous sequence among the various rock types of the shield. Some geologists, however, make a distinction between the massive crystalline rocks, which they correlate with the Archean, and the metamorphic schistose types that are classed as Algonkian. The base of the Algonkian would be a conglomerate.

An analogy appears to exist between the massive crystalline rocks of Ethiopia and the "Dahomeyan" of French West Africa on the one hand, and between the schistose metamorphic rocks and the "Birrimian" of Gold Coast (Ghana), on the other hand.

The crystalline basement of Ethiopia is of particular interest from the fact that it contains almost all the known mineralization of the country, and notably gold and platinum.

Triassic, Jurassic, and Cretaceous sedimentary rocks are absent from the western part of Wallaga province where the platinum occurs and they will be discussed only briefly.

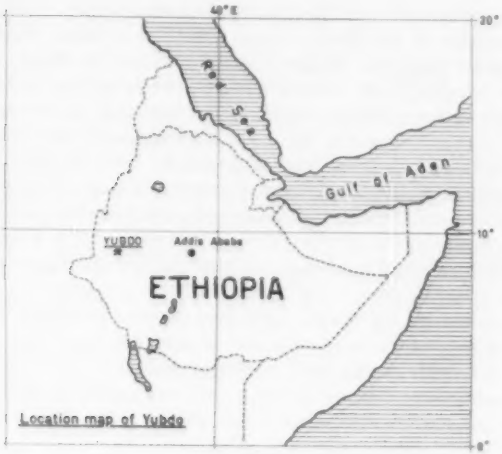

FIG. 1.

Deposition in Ethiopia began in Triassic time with the Adigrat sandstones, of continental origin (comparable with the upper Karroo), transgressive upon the crystalline basement. This transgression, however, did not reach the Southwestern part of the country. In Somaliland, the shield was invaded transgressively by a somewhat different series, the Lugh Series, consisting of sandstones, gypsiferous shales, and siliceous marls.

In Jurassic time, the flooding in the North and in the East continued and clear-cut marine formations make their appearance, with different names according to the area: Antalo limestones, Lagadjima limestones, Binin limestones or Series of Bardera.

The passage from Jurassic to Cretaceous is marked by a strong recession of the sea from the northwest toward the southeast, accompanied by the formation of continental sandstones (Nubian sandstones). This emergence affected north and central Ethiopia, but the eastern part (including a part of Somaliland), remained submerged until Eocene time.

As a consequence of this marine recession at the end of the Jurassic, the sedimentary rocks occur at the base of the Ethiopian plateau as a wedge intercalated between the crystalline basement and the subhorizontal flows of trap rocks. The thickness of sediments is much less in the northwest (Tigre = 200 m) than in the southeast (Somaliland = 1,000–2,000 m).

The volcanic trap rocks constitute a large proportion of the Ethiopian plateau and extend to its southern and western reaches. They form great, subhorizontal lava flows up to 1,000 to 2,000 m thick in places. One can distinguish the Ashianghi Serie, which is the older and consists essentially of basalts, and the Magdala Serie which is the younger and includes trachytes, liparites, and also some basalts.

According to Gregory (3), the Ashianghi lavas would be contemporaneous with the formation of the East African Arch, and the first fractures along the upper part of that arch (upper Cretaceous). The main eruptive phase, including the alkaline lavas and basalts of the Magdala Serie occurred in Miocene time. It was during the Miocene that large fractures were formed that give rise to the collapse of the East African Arch, thus creating a great graben, the Ethiopian Rift Valley, which from lake Rudolf to the Gulf of Aden, separates the Ethiopian Plateau from the Somali Plateau.

The volcanic rocks later in age than the formation of the Ethiopian graben represent the continuation of the volcanic activity during a second phase of fracturing, which affected the marginal zones of the Ethiopian Rift Valley in Pliocene time.

These rocks include the Awash lavas and those of the Aden Series: basalts, trachytes, liparites, which are but a few tens of meters thick, in most cases, and which cover parts of the bottom of the graben. Those formations form some well preserved volcanic cones. The volcanic activity persisted in Pleistocene time and up to Recent times, forming the Afar volcanoes, some of which still show active fumaroles (Dofane).

The Tertiary and Recent sedimentary rocks are found mostly in Eastern Ethiopia, in the coastal areas of the Red Sea and Indian Ocean, and in down-faulted zones.

Calcareous or arenaceous Eocene formations cover a vast area of Somaliland. In Miocene time, some sandstones, marked by fossil wood, are found as intercalations in the volcanic Magdala. The Pliocene and Pleistocene are characterized by lacustrine and fluvial deposits. Finally, in Recent time, the bottom of some main valleys with gentle slope has been partially lined with alluvium, and recently emerged marine deposits are found in some coastal parts of Eritrea and Italian Somaliland.

Structural Geology.—It has been stated above that the Precambrian formations of the crystalline basement displayed a NE-NW fold trend, with steep dips, as a rule. This Precambrian mountain building is probably Huronian in age as is the case for similar formations in West Africa.

After Precambrian time, further folding of the mountain building type is absent from Ethiopia and all formations overlying the crystalline basement show a subhorizontal attitude, save for some localized folding.

On the other hand, starting in late Cretaceous, the country has been submitted to intense large-scale fracturing, which led to the formation of the graben of the Awash and of the lakes, this graben being a part of a branch of the Great Rift Valley.

The transgression, which begins in Ethiopia at the beginning of the Cretaceous, gave rise to an emerged arch through the central part of the country, whereas the eastern part remained submerged. The first stage of fracturing along the upper part of the arch took place at the end of the Cretaceous, and a second one, during lower Pliocene time, gave rise to the formation of the Ethiopian Rift Valley. The graben thus created is some 100 km in width in the southwest, toward lakes Stefanie and Rudolf. Toward the northeast in

the direction of lake Abbaya, its width is only 50 km, but farther on, it widens out into the Awash valley.

To the North of the Dankali desert, the Rift Valley breaks up into two branches, one toward the north in the direction of the Red Sea, the other toward the east in the direction of the Gulf of Aden. Between these two branches lies the small Dankali horst.

It is to be noted that the sedimentary and volcanic formations that make up the great Ethiopian horst to the northwest of the Rift Valley are roughly horizontal, whereas those of the smaller Somali horst has a gentle tilt toward the southeast.

The formation of the Rift Valley was accompanied by much subsidiary fracturing, some of which gave rise of the Omo valley graben, North of lake Rudolf.

In lower Pleistocene time, the last subsidiary fracturing took place. The rising of that part of the African continent, has continued slowly to this day, as demonstrated by the recent marine deposits, in emergence along the coasts.

In the Birbir valley of western Ethiopia, with which we are concerned, the volcanic trap rocks rest directly on the crystalline basement, and sedimentary rocks are lacking.

The trap rocks consist essentially of basalts, trachytes and volcanic tuff. They form subhorizontal layers up to several hundred meters thick. The main summits, Tullu Wallol (3,300 m) west of the Birbir, and Tullu Djergo to the east, probably represent old, eroded volcanoes.

The volcanic layers have been deeply eroded by the Birbir river, which, along most of its course, has cut into the crystalline basement. The eastern volcanic section (Tullu Djergo) is linked to the High Ethiopian Plateau, through Gore and Djimma. The western section (Tullu Wallol) constitutes an isolated massif extending toward the Sudan boundaries.

At Yubdo, those two sections lie close together and the crystalline basement appears only along a narrow corridor, 5–6 km in width, flanked by the Ghangi basalts on the left bank and those of Kope on the right bank. This band of crystalline formations, which includes the bottom of the Birbir valley and the Yubdo and Soddo (or Sodu) hills on the right bank, is of particular interest, as it includes the ultrabasic rocks that have given rise to the primary platinum deposit.

THE YUBDO DEPOSIT

On the east slope of Yubdo hill, facing the Birbir river, is an elliptical outcrop of dunite of about 1 by 2 km in area. On the opposite slope, or west flank of the hill, is another, similar, though smaller, dunite exposure.

Originally, the dunites were capped by lateritic eluvium that masked them, but the first workings (ca. 1926) disclosed a bedrock covered with a crust of reddish alteration, a few centimeters to a few decimeters thick, and of a characteristic mamillary aspect.

The Yubdo dunite is similar to that of the Urals. In its fresh state, under its alteration crust, it is dark green in color with a typical greasy luster. Under the microscope, one can observe olivine in rounded, colorless

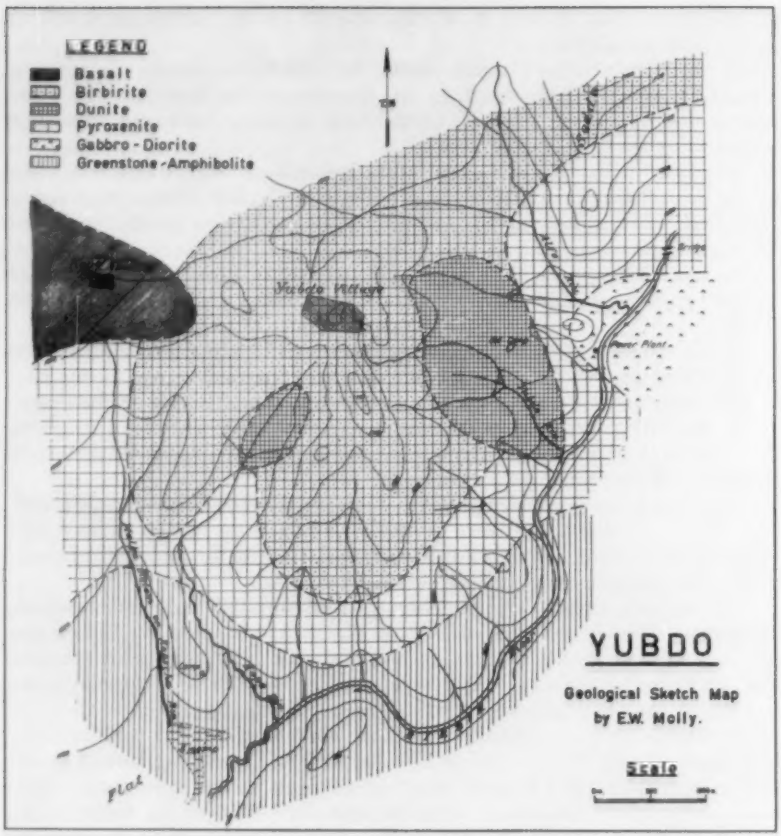

FIG. 2.

grains, forming a tight aggregate, with small grains of chromite scattered erratically throughout the groundmass. The olivine is invariably serpentinized, with the change taking place along cracks in the mineral. At Yubdo there are no nests or schlieren of chromite such as are found in the Urals.

An average analysis of the dunite shows (4):

SiO_2	36.55
Fe_2O_3	7.05
FeO	4.25
Cr_2O_3	0.35
MgO	43.51
H_2O	8.61
	100.32

The rock contains neither nickel nor titanium. Its chemical composition is identical with that of the dunites from the Urals, with a relatively low percentage of iron oxides. It thus has nothing in common with the platinum bearing hortonolite-dunites of South Africa.

Very hard, brownish rocks of quartzitic aspect and with a splintery fracture, cap the dunites and form the top of the hills of Yubdo and Soddo. We termed those rocks "birbirites," with the late Professor L. Duparc, in 1927. This was a new type of rock, which was again identified later, under similar conditions, by Duparc in Yugoslavia.

The birbirite results from a deep alteration of the dunite and consists almost exclusively of secondary silica and iron oxides. Under the microscope, the rock shows a network of small areas of iron oxide (limonite) enclosing colorless material that consists of fine-grained quartz and fibrous chalcedony, and a little associated isotropic matter.

An analysis of this rock shows (5):

SiO_2	88.20
Al_2O_3	traces
Fe_2O_3	9.01
Cr_2O_3	0.86
FeO	0.28
CaO	0.24
MgO	0.30
Loss in ignition	1.50
	100.39

A comparison of this analysis with that given previously shows that all the magnesia contained in the olivine has been removed, whereas the silica recrystallized as secondary quartz and chalcedony. The main fact is the concentration of chromite, which demonstrates the dunitic origin of the birbirite. Through the almost total elimination of magnesia, the remaining constituents have undergone a concentration of about 2.4, the Cr_2O_3 thus rising from 0.35 to 0.86 percent.

Platinum, which is present in very small quantities in the dunite (generally less than 0.05 gm per ton), has undoubtedly been concentrated in the same ratio. The tenor of the birbirites is still too low, however, to make the rock mineable.

Other observations also confirm the dunitic origin of the birbirite:

a—The argillaceous eluvium capping the dunite and that capping the birbirite are exactly similar and platinum-bearing.

b—Some streams flowing exclusively through birbirites carry platinum.

c—The contact birbirite-dunite is not clear-cut, and intact dunitic cores are found in the midst of the birbirite.

d—We have observed that since our departure in 1928, the mining operations had removed the birbirite in places, leaving the underlying rock bare. The area of exposed dunite is thus a little more extensive than it was thirty years ago.

The dunitic origin of the birbirite has been accepted by most of the geologists who have visited Yubdo. However, some have attempted to explain the high content in silica by subsequent hydrothermal additions. However, it seems that the simple concentration *in situ* of the dunite, through removal of the magnesia, can explain the high silica content of the birbirite.

From the foregoing discussion, it may be seen that the birbirite capping the Yubdo and Soddo hills constitutes a "hat," on top of the primary deposit. The two outcrops of dunite are but a single body and the primary dunite and birbirite, extends over an area of about 6 by 2 km.

This primary deposit is surrounded by a more or less continuous belt of pyroxenites, which are well exposed at the bridge over the Birbir and along the right bank of the river, as well as along the middle part of the course of the Kope. Farther out from the pyroxenites, there are gabbros, particularly near the mouth of the Alfe river, as well as amphibolite schists and greenstones along the lower part of the Kope river.

This concentric arrangement of dunites, pyroxenites and gabbros recall that of the primary platinum deposits of the Urals. The occurrence is that of an intrusive basic dike, the basic character of which increases from the outside inward. On the other hand, the Yubdo deposit shows no similarity with those of South Africa in which platinum is associated with mineable norite, whereas at Yubdo and in the Urals, only the eluvium and alluvium are mineable.

L. Duparc, in his treatise on platinum (6), has shown that when the deposit is of the classical type, that is showing a concentric arrangement of the dunite, pyroxenite and gabbro, all of the platinum is localized in the dunite, whereas the pyroxenite is barren. On the other hand, where the dunite is absent, some platinum may occur in pyroxenite, under certain conditions. It thus seems that during differentiation of the basic magma, the platinum becomes concentrated in the most basic part of that magma, in the heart of the intrusive mass.

It is extremely rare to observe visible platinum in the dunites, partly because of the very small amount present, and partly because of the extremely irregular platinum distribution in the original rock. In fact, no visible platinum has ever been noted at Yubdo, but from the nature of the platinum collected from the lateritic eluvium capping the primary deposit, it appears that the platinum was not associated with the chromite.

This eluvial platinum occurs as blackish, small grains showing mamillary surfaces and lined with limonitic cavities, and with no apparent crystal form. They look like metal droplets that became consolidated among olivine crystals of which they kept the imprint.

The following is an analysis of this rough eluvial platinum, after sorting it out with the lens from the free gold that was almost always in the pan concentrates at Yubdo (4):

Platinum	79.48
Iridium osmide	1.41
Iridium	0.82
Rhodium	0.75
Palladium	0.49
Gold	0.49
Iron	16.50
	99.94

Another analysis, reported by Usoni (2) for metal collected subsequently, shows a 70.97% Pt and 4.44% Au content. These values are analogous to those of some platinum of dunitic origin from the Urals given by Duparc as varying from 60.39–84.60% Pt.

PLATINIFEROUS ELUVIUM

The lateritic eluvium capping the primary deposit of Yubdo occurs as a dark red clayey layer, ranging in thickness from 2 to 10 m, with an average of about 6 m. This eluvium was partially worked by the natives in the old days, long before the discovery of platinum, as it contained a little gold. However, the workings in the eluvium on both sides of Yubdo hill, and particularly on the east side, became really important only after the discovery in 1924 and after the installation of a permanent European camp in the center of the deposit. At first, owing to the lack of access for the transportation of mechanized equipment, only hand panning was used. Much of the operation consisted in re-panning the tailings left by the ancient gold panners who had rejected the platinum. Some very high-grade tailings were then treated but they were rapidly exhausted. In 1926, sluice-boxes made of local wood were set up in about the center of the main dunite exposure. They were fed through a race located as high as possible on the slope of the hill and which received its water from small tributaries of the right bank of the Birbir.

In the center of the deposit, the grade of the eluvium was at first from 0.3 to 0.5 mg of gross platinum per cubic meter. Later on, as the mining moved away from the dunitic center, the grade fell off and was only 0.11 gm/M^3 in 1938, according to Italian records (2). According to the same statistics mentioned by Usoni (2), the production at Yubdo between 1926 and 1938 was of 1575 kg of gross platinum extracted from 9.4 million cubic meters of eluvium. After 1938, the records are fragmentary, but considering the rapid decline of the operation after 1940, the total extraction for the period 1926–1956 is about 2,000 kg of platinum.

In 1957, I found at Yubdo only some 20 workers operating for the Ethiopian Government, while formerly the labor force was at times in excess of 2,000 workers. It is true that the operation was never highly mechanized and the small concentrator built on the eve of the war was destroyed shortly thereafter.

The platiniferous eluvium of Yubdo has been worked, though in an incomplete fashion, over an area of about 2 sq km with an average thickness of 6 m. Various authors have attempted to estimate the remaining reserves, but the ground has been so greatly disturbed by irrational mining that such

estimates are quite problematical. They vary from 500 to 1,600 kg of gross platinum in only the Yubdo sector.

The Soddo eluvium, which constitutes the northeast extension of the deposit, has not been estimated nor sampled with accuracy. The Soddo sector has been much less worked than that of Yubdo and it is probable that the grade of its eluvium proved to be lower.

The presence of gold in the eluvium capping the dunites and birbirites is fairly unusual. Some small basalt dikes cut the dunites, but primary quartz veinlets are seldom found. All quartz fragments seen in the eluvium are of secondary origin, derived undoubtedly from the birbirites. As it is difficult to admit that the dunites are gold-bearing, it is possible that there exist at Yubdo some quartz veinlets that have escaped detection. On the other hand, the presence of gold in the Birbir alluvium, near Yubdo, is not unusual as the river flows through crystalline basement rocks cut by numerous quartz veins. At Tullu Kapi, about 10 km north of Yubdo, there is a gold vein that we investigated in 1926.

The gold mining in the Birbir watershed and in that of the Dabus, farther to the north, goes back to very ancient time and it is not impossible that those areas of Ethiopia, which were in contact with ancient Egypt through the Upper Nile valley, provided important quantities of precious metal to the Ancient World (7). The presence of some grains of rough platinum found in certain Egyptian tombs would seem to confirm this hypothesis.

PLATINIFEROUS ALLUVIUM

The alluvium is of three different types:

a—That found in the small tributaries of the right bank of the Birbir, and which has traveled through the Yubdo deposit.
b—The alluvium along the actual course of the Birbir.
c—That of the terraces and ancient beds of the Birbir.

Eluvium from the small tributaries, Alfe, Yubdo and Kope, represent only a very limited tonnage of gravel, as the streams have a small flow and a restricted watershed. The eluvium of the Yubdo, which was worked at an early stage, has been almost completely removed, as it was notably richer than the eluvium. It is the same for the Alfe, which was worked later.

There remains only small reserves located in the lower flat of the Kope, over a length of 1 km. Some little pits put down in 1957, have shown, under an upper layer of sand and clay of 2 m in average thickness, a gravel bed of 0.5 to 1.0 m with grades of 0.25 to 0.83 gm/M³ for platinum, and of trace to 0.20 gm/M³ for gold.

The investigation of the alluvium of the present bed of the Birbir, as well as of that of the terraces and old beds was begun as early as 1926. However, the prospecting was quite restricted, as we lacked the necessary equipment to investigate the gravel below the hydrostatic level. A siberian shovel, built on the spot, allowed some sampling on the bottom of the Birbir, some distance downstream from the mouth of the Yubdo. I have not kept the

results but, as far as I can remember, the grade for platinum was in excess of 1 gm/M³ with a notable proportion of associated gold. The platinum here was quite different from that of the eluvium and occurred as much smaller grains, of rounded shape and with a steel gray luster. As this section of the Birbir was torrential and could not be dredged, the prospecting has been pursued farther downstream and it is in this process that the great flats and old beds of the Birbir, immediately downstream from the Kope, were discovered.

This region, which is uninhabited and difficult of access, and crossed only at rare points by some elephant hunters, was explored in 1927. It showed that, between the mouth of the Kope and the great rapids of Uris, the Birbir meanders across a great flat in which it is possible to recognize old river beds and terraces.

Fairly important old native workings have been located in an old bed of the Birbir, some distance downstream from the Kobe. Those show that one could expect a gravel bed resting on the bedrock, lying below the hydrostatic level and overlain by 3 to 6 m of barren material.

As it was impossible at that time to reach the gravel bed near the bedrock, either in the river or in the swampy old beds, no indications had been obtained on the grades of platinum and gold, and on the tonnage available. This is why, during our examination of 1957, after having found that the eluvium at Yubdo was nearly exhausted and offered relatively limited possibilities, save perhaps on the Soddo side, we had planned to prospect the old beds and terraces of the Birbir, downstream from the Kope.

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July 18, 1958

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STRUCTURAL HISTORY OF THE BEAVERLODGE AREA

J. A. CHAMBERLAIN

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ABSTRACT

The Precambrian rocks of the Beaverlodge area, northern Saskatchewan, are divisible into two broad units; (1) the highly folded and extensively granitized Tazin group unconformably overlain by (2) the synclinally folded Athabasca series. These rocks are cut by three major faults and evidence is presented to show that two of these, the St. Louis and ABC faults, are probably extensions of the same break despite a bend of eighty degrees between the two prolongations. Age of faulting is discussed and it is concluded that much, if not all, of the fault movements occurred in post-Athabascan time. A method is described by which quantitative estimates of the net-slip on the St. Louis-ABC fault are calculated. Movement is normal, the net-slip roughly four miles. A minimum normal dip-slip component of movement on the Black Bay fault is found to be of the same order of magnitude. A four-stage tectonic history of the area is presented in which two periods of crustal shortening alternate with regional, then localized epeirogenic movements. Wherever possible, idealized block diagrams are used to illustrate tectonic events. A table summarizes the tectonic history of the area.

INTRODUCTION

THE Beaverlodge area, comprising some eight hundred square miles on the north shore of Lake Athabasca, ranks as Canada's second largest uranium producing district. The geology and structure of the area have been mapped and discussed by Christie (6) and by Tremblay (14), and earlier workers

for the Geological Survey of Canada carried out reconnaissance work prior to the uranium-rush.

The basement rocks of the Beaverlodge area, exclusively of Precambrian age, are complexly folded and are cut by major faults. At least two periods of deformation have combined to obscure the geologic relations and, as a result, the structural history of the area has not been satisfactorily resolved to date.

This paper offers an explanation for the existing geological and structural features in terms of a tectonic history of the area. The proposed tectonic history is based, in part, on the nature of the movements calculated on the major faults. An attempt is made to distinguish between fact and inference throughout. The initial descriptive sections covering the geology and structure of the area are largely factual. The ideas presented in the sections that follow, dealing with fault movements and tectonic history, are inferences that seem best supported by the available evidence. In a forthcoming paper, an attempt will be made to link the structural control of the pitchblende orebodies of the area to specific phases of regional tectonism. Correlation of regional with local tectonic events is a logical outcome of a study of this kind and may prove of practical value in developing areas of known mineralization as well as suggesting areas favorable for prospecting elsewhere in the district.

GEOLOGY

General Statement.—The rocks of the Beaverlodge area fall into two distinct units. The oldest, the Tazin group, is comprised of granite, alaskite, and gneiss associated with highly folded remnants of sedimentary origin.[1] The Tazin rocks are locally overlain by a series of synclinally folded sediments known as the Athabasca series. A pronounced angular unconformity separates the two units.

Tazin Group.—Rocks of the Tazin group are typical of those found over much of the Canadian Shield. Wide belts of granite and granite gneiss are separated by wedges of highly folded sedimentary rocks. The sediments consist largely of argillitic and quartzitic formations, with local dolomite and conglomerate members.

Despite the highly folded nature of the Tazin sediments and their proximity to large granitic masses, the degree of metamorphism is generally low, or absent altogether. No spacial relationship exists between the degree of metamorphism and the distribution of granitic rocks.

At least fifty percent of the exposed Tazin group consists of a granitic complex ranging from highly foliated gneisses through granites to massive, mafic-deficient rocks best classified as alaskite. The granitic rocks show gradational contacts with many of the older sediments. Most geologists who have worked in the area believe that metasomatism has played an important part in the formation of the granitic rocks.

[1] For purposes of this paper, all rocks of pre-Athabascan age are included in the Tazin group. This oversimplification implies no criticism of Christie's (6) breakdown of the Tazin rocks but is rather used here to facilitate discussion of tectonic events taking place in pre-Athabascan time.

Athabasca Series.—Unconformably overlying the Tazin group, the Athabasca series is made up of conglomerate, arkose and siltstone, locally intercalated with volcanics of basaltic composition. The present configuration of the series in the Beaverlodge area is that of a major syncline some twenty-five miles long and five miles wide at the center (Fig. 1). Structural sections drawn through the syncline indicate that the Athabasca series is roughly 15,000 feet thick in the vicinity of Beaverlodge Lake.

Bedding is clearly defined in the arkose and siltstone formations and is generally coarse, the beds varying in thickness up to two or more feet. Cross-bedding of the torrential type is common in the arkose. Other primary sedimentary structures include ripple marks and polygonal mud-cracks, while pillows are noted in the basalt flows.

At this point, a few remarks should be made regarding the distribution of the Athabasca series elsewhere in the region. South of Lake Athabasca, relatively flat-lying sandstones overlie the basement complex. These sandstones cover approximately 35,000 square miles, an area roughly comparable to that of the Michigan basin. It has been repeatedly pointed out (1, 13, 6) that these vast deposits are equivalent to the Athabasca series in the Beaverlodge area. The present writer is in accord with this view.

STRUCTURE

General Statement.—The strike of the Tazin beds is predominantly northeast, parallel to the axis of regional folding. Schistosity as developed locally in the argillaceous sediments almost invariably parallels the bedding. The foliation of the granite gneisses shows a similar northeast trend.

The structure of the Tazin group is characterized by folds of large amplitude, measuring as much as three miles from crest to crest. The Goldfields syncline, described by Christie (6) is probably the largest single fold in the area. This trough plunges twenty-five degrees southwest. Additional regional folds are shown in Figure 1.

Locally, the major folds are transected by minor folds the axial planes of which strike north to northwest. Such belts of cross-folding have been noted by Campbell (3) along the St. Louis fault and the writer has observed similar belts at several locations east and north of Beaverlodge Lake.

The strongest structural breaks in the area are the St. Louis and Black Bay faults, both of which strike northeast and dip southeast fifty to sixty-five degrees. A third important break, the ABC fault, strikes northwest and dips 50° SW. These faults carry well-defined gouge-zones and are locally paralleled by bands of brecciated or mylonitized wall-rock. Close to the faults, however, it is common to find well-bedded Tazin sediments that show no evidence of crushing, shearing or crenulation. Conversely, wide zones (up to 1,000 feet) of breccia and mylonite occur elsewhere in the area that show no discernable relation to the faults.

Hydrothermal alteration, much of which is in the form of hematitization, is associated with faults throughout the area. The rocks are locally intensely affected by this alteration, particularly in localities where pitchblende occurs.

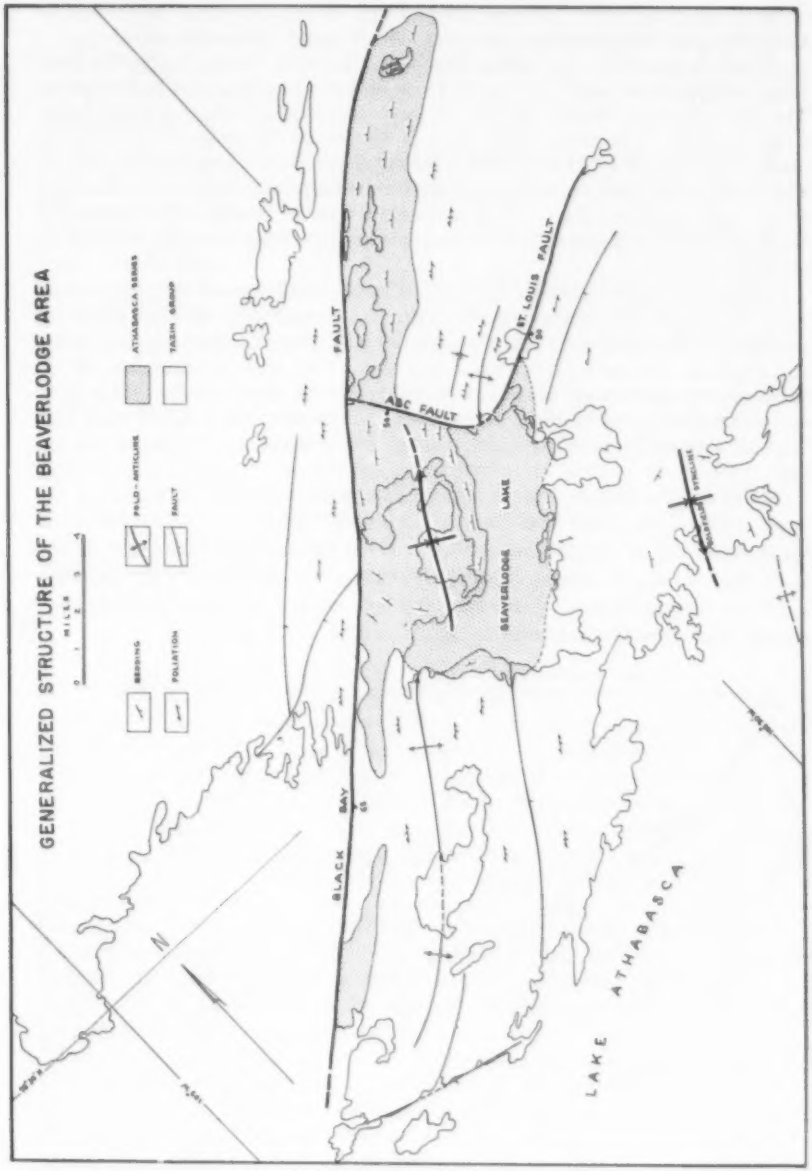
GENERALIZED STRUCTURE OF THE BEAVERLODGE AREA
MILES
ATHABASCA SERIES
TAZIN GROUP
PALEO-ANTICLINE
FAULT
BEDDING
FOLIATION
FAULT
ABC FAULT
ST. LOUIS FAULT
BEAVERLODGE LAKE
BLACK BAY
LAKE ATHABASCA
N

FIG. 1.

It is to be emphasized that no rocks have entirely escaped hydrothermal alteration and mineralization, including the younger Athabasca series.

Black Bay Fault.—The Black Bay fault, shown in Figure 1, extends from Lake Athabasca to north of Anne Lake, a distance of about twenty-five miles. The fault dips an average of 65° SE and is characterized by a remarkably straight scarp. The strike of the fault is parallel to the strike of the foliation of the Tazin rocks which form the footwall of the fault throughout its length. The rocks of the hanging wall are overlain for the most part by the Athabasca series, and the Black Bay fault thus forms a contact between the two major lithologic units of the area. The fault plane carries up to twenty inches of plastic gouge.

St. Louis Fault.—The St. Louis fault has a known strike-length of about eight miles and dips uniformly 50° SE. So consistent is the dip along its straight portions that the intersection of the fault plane by diamond drill holes can generally be predicted within a few feet. The fault is characterized by the presence of a well-defined zone of highly plastic, impermeable gouge with an average thickness of eight inches. Rocks of both the hanging wall and footwall are locally brecciated and crushed for upwards of fifty feet from the fault.

ABC Fault.—Figure 2 shows the surface relation of the St. Louis to the ABC fault. It is noted that the St. Louis fault shows a weak tendency to curve westward as it approaches the shore of Beaverlodge Lake and at the same time its dip decreases from fifty to forty-five degrees. This decrease in dip has been confirmed by diamond drilling and is of significance in explaining the relation of the St. Louis to the ABC fault.

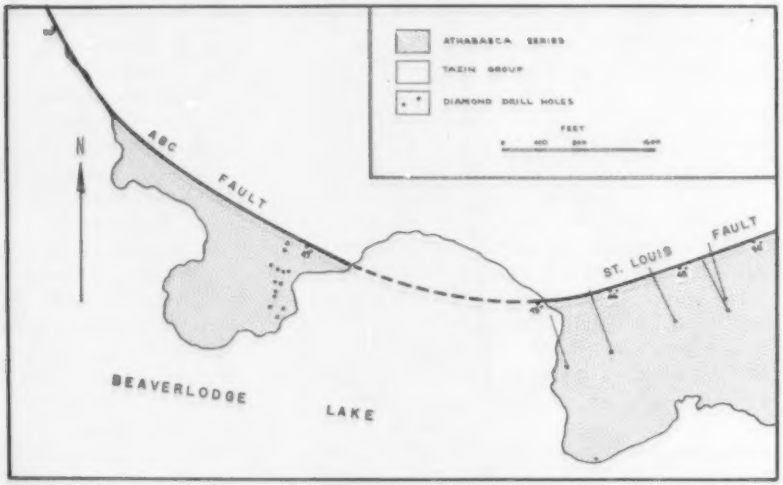

FIG. 2. Detail of probable bend of the St. Louis-ABC fault.

The ABC fault cuts across the north end of Beaverlodge Lake, roughly at right angles to the St. Louis fault. A number of lines of evidence support the assumption that the ABC and St. Louis faults curve into one another and are one continuous structural break. The evidence for this assumption is summarized below:

1. Along its straight portions the ABC fault dips 50° SW, but as it nears Beaverlodge Lake it shows a decrease in dip similar to that of the St. Louis fault, mentioned above.
2. Both faults separate Athabasca rocks in their hanging walls from Tazin rocks in their footwalls.
3. Along their straight portions, both faults dip fifty degrees southward.
4. Both faults exhibit several inches of gouge along a major fracture, accompanied by local zones of breccia and mylonite with intense hematitization of the wall-rocks.
5. An electromagnetic survey was run across the ice of Beaverlodge Lake in the spring of 1956 in an effort to locate the prolongation of the St. Louis fault. No crossovers indicating a conductive break were obtained. Because the survey did not pick up the St. Louis fault, this is taken as evidence that the fault does not extend straight out into the bay, but rather curves westward along the shoreline. It is doubtful that there was a weakness in the survey because of former excellent results obtained in tracing the St. Louis fault across other lakes, using the same equipment.

ORIGIN OF THE BEND OF THE ST. LOUIS-ABC FAULT

If the St. Louis and ABC faults are a continuation of the same break, and the above evidence points strongly toward the validity of this assumption, it becomes necessary to explain the origin of the bend of about eighty degrees between the two extensions. Two possibilities suggest themselves: (1) the bend is a primary structural feature, present at the time of faulting, or (2) the bend was formed after faulting, i.e., the St. Louis-ABC is a folded fault.

On the basis of field evidence, the writer believes that the bend originated at the time of faulting. The main argument in support of a primary bend is the fact that the bedding, lineation and foliation of the Tazin rocks show little tendency to deviate from their regional northeast trend in the vicinity of the bend. Similarly, the bedding of the Athabasca rocks strikes consistently northeast. If the bend were caused by the folding of an originally straight break, such movement would involve the country rocks and would be revealed by a tendency of the regional structural trends to wrap around the nose of the bend. No such deflection exists.

Causes of large-scale deflections of regional faults are poorly understood. They are probably controlled by the action of regional stresses operating in conjunction with heterogeneities of basement rocks or zones of weakness in the sub-crust. For purposes of this paper, the underlying cause of the bend of the St. Louis-ABC fault is attributed to one or more of these factors and will not be considered further.

AGE OF FAULTING

A solution of fault movements within the Beaverlodge area depends to a large extent on the age of the Athabasca series relative to the age of the regional faulting. If fault movements are of pre-Athabascan age, no use can be made of the outline and distribution of Athabasca rocks in working out fault movements. On the other hand, if fault movements are of post-Athabascan age, it is possible to make quantitative estimates of movements on the two most important breaks in the area, the Black Bay and St. Louis-ABC faults.

Some controversy has been expressed by earlier workers with reference to this question of pre- or post-Athabascan faulting. It will therefore be appropriate to outline the evidence on which their conclusions are founded.

Alcock (1, p. 155) in a section entitled "Post Athabascan Faulting," assumed that faulting took place after deposition and consolidation of the Athabasca series. His reasons for making this assumption were based on a study of the general geology and structure of the region as well as on the fact that faulting unquestionably took place after folding, metamorphism and granitization of the Tazin rocks.

According to Smith (13) the Athabasca series was deposited contemporaneously with, and as a result of, regional faulting. Smith draws a comparison between the Athabasca rocks and those of the Newark series where "detritus from the mountains rushed into the structural troughs formed by fault blocks." He expands his ideas on the contemporaneity of faulting and sedimentation by suggesting that "As the compressive stresses were released, the area uplifted and was rent by many normal faults. The tectonically active source rocks . . . were swiftly denuded and the detritus was rapidly deposited in the structural basin and plains between the mountains. Block faulting continued during and following deposition of the Athabasca rocks."

Christie (6) believes that some faulting occurred in post-Athabascan time but suggests that movement also took place prior to deposition of the Athabasca rocks. Evidence for pre-Athabascan fault movement is found by both Smith and Christie in the mylonitized granitic pebbles, derived from the Tazin group, that are found locally in Athabasca conglomerates.

The writer agrees with Smith and Christie in that some pre-Athabascan faulting is possible, but cannot concur with Smith that normal faulting was the *cause* of deposition of the Athabasca series. Furthermore, the writer believes that sufficient geological and structural evidence exists to point to an unequivocal post-Athabascan age for at least a large part of the regional fault movements.

Postulations of pre-Athabascan faulting appear to be supported by the presence of mylonitized pebbles in the Athabasca conglomerate, the assumption being that these were formed by crushing of Tazin rocks during pre-Athabascan movement along the major faults. An alternative explanation, however, can be suggested for the origin of the mylonitized pebbles. As mentioned previously, large areas north and east of Beaverlodge Lake are comprised of brecciated and mylonitized Tazin rocks that show no relation

to major faults. Christie himself states (p. 67) that where "not forming a definite fault or crushed zone, the zones of crushing commonly outline lens-shaped areas of less-crushed gneiss of all dimensions from the augen structures seen under the microscope or in the hand specimen, to lens-shaped areas of gneiss 1 foot, 50 feet, or 1,000 feet long. Less extensively mylonitized or crushed areas occur elsewhere throughout the map-area, and everywhere the pre-Athabasca series rocks show at least some microscopic evidence of crushing . . . ." Thus, there seems no reason to postulate pre-Athabascan fault movement to account for the presence of mylonitized pebbles in an area that has experienced the effects of dynamic metamorphism on a regional scale.

Evidence in support of post-Athabascan fault movement is listed below:

1. The Black Bay and St. Louis-ABC faults unquestionably cut Athabasca rocks. Structural sections drawn at right angles to the strike of the Athabasca rocks, as shown in Figure 4, make this clear.

2. If faulting occurred before and during deposition of the Athabasca rocks, folding of these rocks into their present synclinal configuration must have occurred after faulting. This sequence of tectonic events is unlikely on the basis of tectonic studies elsewhere in the world where normal faulting is generally found to follow regional folding and metamorphism of basement rocks.

3. Post-Athabascan faulting is confirmed by truncation of the bedding of Athabasca rocks by the ABC fault, a situation difficult to conceive if these sediments were deposited in a trough formed by subsidence along this fault.

4. Hydrothermal alteration and pitchblende mineralization are associated with regional faulting. If faulting preceded deposition of the Athabasca series, alteration and mineralization of these rocks would not be expected. Thus, the presence of crosscutting pitchblende veins accompanied by local, intense hematitization of the wall-rocks in the Athabasca series suggests that these rocks were already consolidated and folded prior to faulting and mineralization.

5. The great areal distribution of the Athabasca series south of Lake Athabasca does not suggest an origin dependent upon localized subsidence of fault blocks, but rather supports the concept of large-scale epeirogenic movements in which portions of the earth's crust were lowered while adjacent regions were uplifted.

The above evidence leaves little doubt that extensive faulting took place in post-Athabascan time. Although the writer admits that there is no apparent objection to assuming that some faulting occurred in pre-Athabascan time, there is little to be gained by making such an assumption purely on the grounds that there is no objection against it.

FAULT MOVEMENTS

Geologists who have worked in the Beaverlodge area agree that regional faulting appears to be characterized by large normal components of movement. Evidence in support of normal movement is found in the preservation of Athabasca rocks on the hanging wall sides of the major faults. Evidence

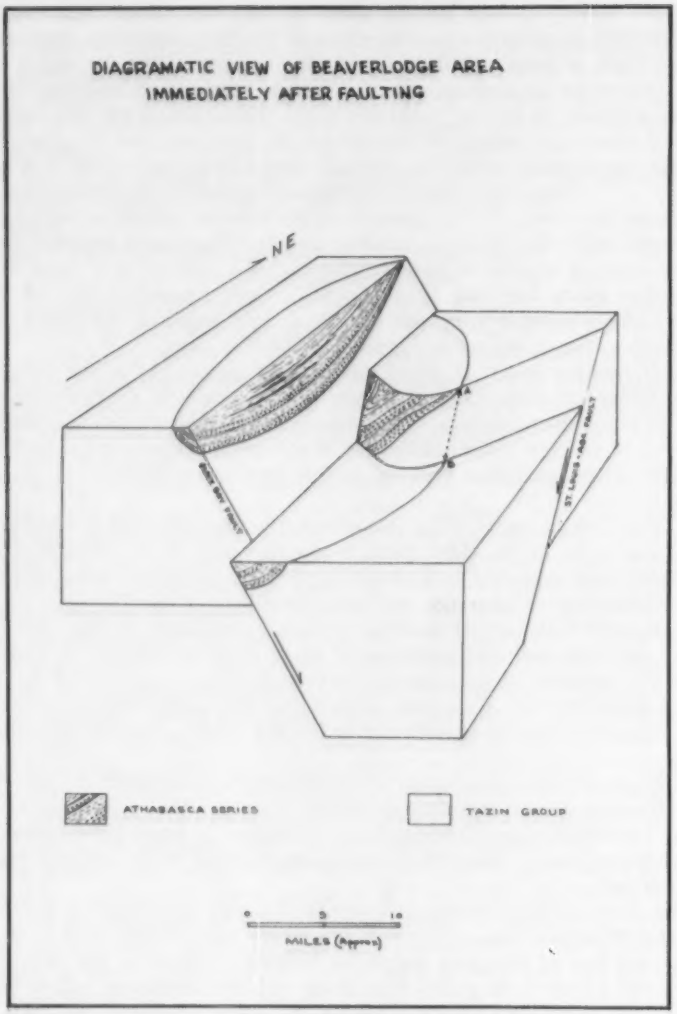

FIG. 3.

also comes from the fact that movements on certain minor faults west of Beaverlodge Lake have been worked out in some detail (13) and have been found to be essentially normal.

Additional evidence of normal movement is suggested by the distribution of granitic and sedimentary rocks of the Tazin group. This is based on

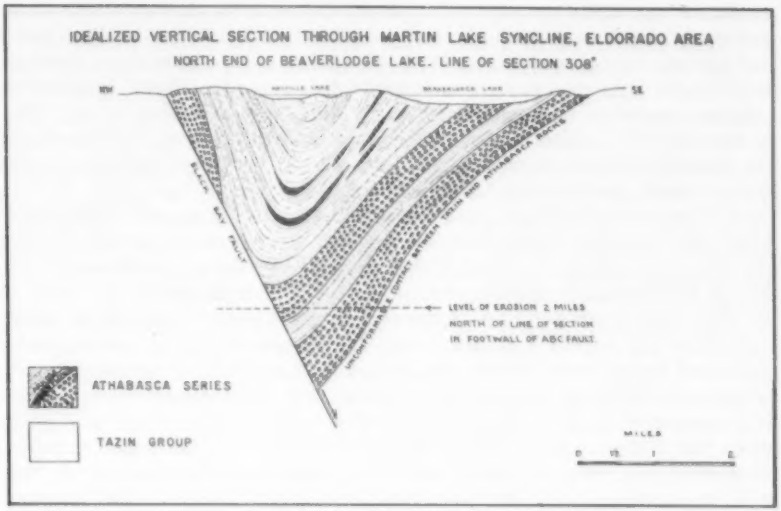
IDEALIZED VERTICAL SECTION THROUGH MARTIN LAKE SYNCLINE, ELDORADO AREA
NORTH END OF BEAVERLODGE LAKE. LINE OF SECTION 308°
NW
SE
BLACK BAY FAULT
LEVEL OF EROSION 2 MILES NORTH OF LINE OF SECTION IN FOOTWALL OF ABC FAULT
ATHABASCA SERIES
TAZIN GROUP
MILES
0 1/2 1 2

FIG. 4.

the theory that the granitic portions of the Tazin group were at one time more deep-seated than were the sediments. From this it follows that deeper erosion of the basement has resulted in those areas where the exposed rocks are mainly granitic. Thus, normal movements are suggested by the fact that the surface exposures west of the Black Bay fault and north of the St. Louis-ABC fault are about ninety percent granitic, while east and south of these same faults granitic rocks make up only about thirty percent of the exposed Tazin rocks.

However much agreement there may be among geologists regarding normal movement, no quantitative estimate of the net-slip on any of the major faults has been put forward. Christie (5) estimates eleven hundred feet of apparent right-hand horizontal movement on the St. Louis fault, based on a study of contacts of Tazin rocks on both sides of the fault. Smith states that the separation of Athabasca sediments indicates apparent left-hand movement along the same fault.

In the vicinity of the Eldorado mines, various Tazin rocks have been studied in both the hanging wall and footwall of the St. Louis-ABC fault. In many cases, contacts between rock-types are gradational and their attitudes ill-defined. Masking effects of hydrothermal alteration have further obscured the geologic record so that it now seems doubtful that movement on the St. Louis-ABC fault can be satisfactorily resolved from a study of displaced Tazin rocks. It is even less likely that an estimate of the movement on the Black Bay fault can result from a study of Tazin rocks because this fault parallels the strike of the Tazin gneisses along its entire length.

In contrast to the complex and confused nature of the geology of the Tazin group, the Athabasca rocks are clearly defined both by their distinctive facies and by their unconformable relation to the underlying Tazin group. Furthermore, the Athabasca rocks are unmetamorphosed and have been subjected to only one period of deformation. Thus, it seems logical to look to the Athabasca rocks for evidence of post-Athabascan fault movement. This approach is especially attractive because most, if not all, of the regional faulting appears to have taken place in post-Athabascan time.

The writer has worked out a net-slip for the St. Louis-ABC fault using two rather clear-cut features associated with the Athabasca rocks; (1) the plunge and bearing of the bend of the fault and (2) the dip of the basal contact of the Athabasca series across the eastern half of the syncline.

The bend of the St. Louis-ABC fault plunges forty-three degrees on an azimuth of 200 degrees. It seems clear that movement on this fault is rigidly controlled by its bend of eighty degrees along strike. Consideration of the geometrical relations between the hanging wall and footwall blocks reveals that movement of either block is required to be either directly up or directly down the plunge of the bend. This would not be so if the fault extensions showed a constant curvature along strike away from the bend for, in this case, it would be mechanically possible for the hanging wall block to grind past the footwall block laterally (strike-slip movement) as well as to ride up or down the curved fault plane (reverse or normal movement). However, both lateral extensions of the St. Louis-ABC fault away from the bend are remarkably straight. This being the case, only normal or reverse movements are possible on the bend. It is therefore suggested that the net-slip of the fault parallels the bearing and plunge of the bend in question and, for reasons already given, that the hanging wall was downthrown relative to the footwall.

In addition to calculating the probable direction and sense of movement, completion of the fault solution requires that there be some basis for restoring the geology to its position prior to faulting so that a quantitative estimate of the net-slip can be made. Figure 3 is a hypothetical view of the area immediately after completion of faulting. The raised footwall blocks along both the Black Bay and St. Louis-ABC faults are shown intact, before erosion. Point "B" marks the present eastern limit of the Athabasca rocks on the hanging wall side of the St. Louis-ABC fault, while "A" is the imaginary point in the footwall that was adjacent to "B" prior to faulting. If there were some means by which the dip of the unconformable contact between the Athabasca and the Tazin rocks could be established, it would be possible to project this contact up-dip until it intersected the line of net-slip as projected upward from point "B" in Figure 3. The intersection thus obtained would specifically locate point "A" and a quantitative estimate of the net-slip could be determined by measuring the distance between the two points.

The contact between Athabasca and Tazin rocks marks the base of the syncline formed by the Athabasca series. The attitude of this contact can

be examined at two widely differing levels of erosion within the map-area. North of the St. Louis-ABC fault, where deepest remnants of the syncline are exposed, the basal contact dips consistently sixty-five to seventy degrees northwest. South of this fault, where the syncline has been subjected to relatively little downward erosion, the basal contact dips about forty degrees northwest. The surface expression of the syncline south of the fault is such that a structural cross-section can be constructed with some confidence, especially in this case where projections are aided by a knowledge of the attitude of the basal contact at a deeper level of erosion. Figure 4 is such a composite structural section across the syncline south of the St. Louis-ABC fault. The lower one-third of the section is actually taken from the same syncline as it appears north of the fault. Thus, the figure is a combination of two structural sections and, although idealized, is probably reliable in tracing the outline of the basal contact.

The problem of movement on the St. Louis-ABC fault is now essentially solved. It only remains to use the preceding data to arrive at a quantitative estimate of the net-slip. Line "A-B" in Figure 5 is the horizontal projection of the net-slip, parallel to the bearing and plunge of the fault-bend. Point "A" is the intersection of this line with the upward projection of the basal contact. The elevation of point "A" is 2.7 miles above ground-surface, which gives a net-slip of 3.9 miles. At point "B" the dip-slip is 3 miles and the right-hand strike-slip is 2.1 miles. It is of interest to note that the strike-slip component is right-hand along the St. Louis extension and left-hand along the ABC extension. In the vicinity of the bend itself, there is no strike-slip component.

Some comments regarding the probable error of the above figures are warranted. Of the two assumptions on which the solution of the fault problem are based, little more can be said about the controlling effect of the bend of the St. Louis-ABC fault. If the bend exists, the bearing and plunge of the net-slip are established with reasonable certainty.

With reference to the second assumption, i.e., the attitude of the basal contact, it is clear that no two geologists would arrive at identical interpretations. Nevertheless, the control imposed by a knowledge of the dip of this contact at two widely differing levels drastically limits the range of allowable attitudes. In addition, the nature of the projection involved is such that the basal contact can show considerable variation without changing the general order of magnitude of the net-slip. For example, consider the case where the basal contact is projected upward at a constant sixty-five degrees. For this case, which may be considered a maximum, the net-slip amounts to 5 miles. Similarly, using a constant dip of forty degrees, which may be considered a minimum, the net-slip amounts to 2.9 miles. It is therefore likely that the net-slip of 3.9 miles, as calculated, is a close approximation of the true value.

In the case of the Black Bay fault, no possibility exists for determining the net-slip by methods already employed because of the fact that no Athabasca

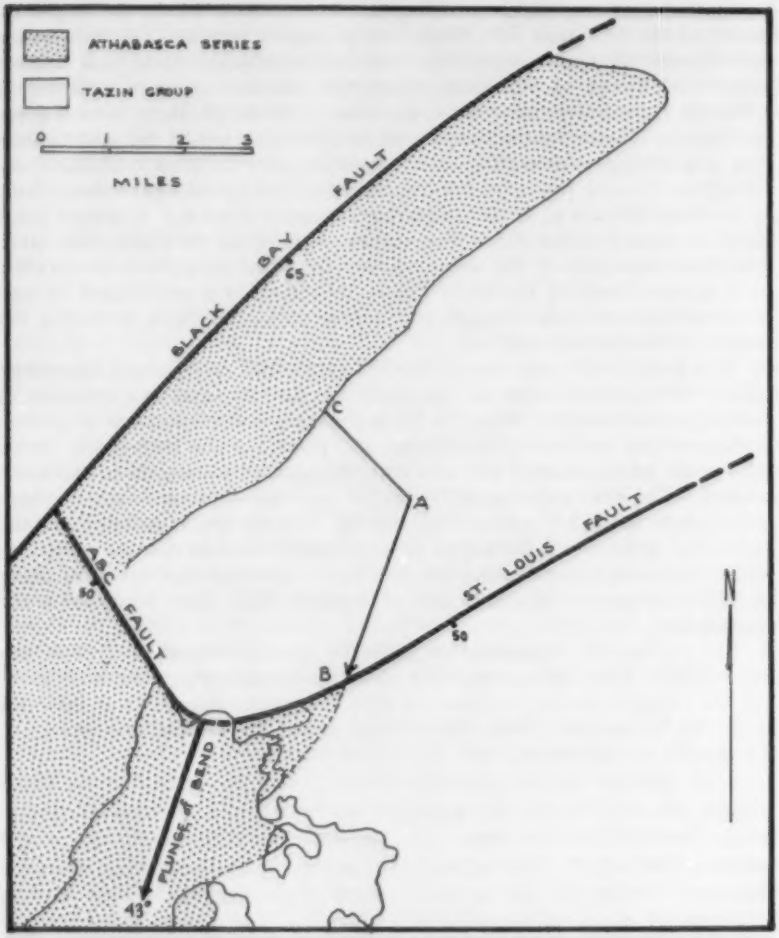

FIG. 5. Method of calculating net-slip on St. Louis-ABC fault. See text for explanation.

rocks occur in the footwall block. However, this very absence of Athabasca rocks in the footwall provides evidence for a quantitative estimate of the minimum dip-slip component. Figure 4 shows Athabasca rocks in contact with the downward projection of the Black Bay fault for a distance of 4.2 miles, which indicates that the hanging wall was downthrown relative to the footwall by at least this amount.

TECTONIC HISTORY

It is postulated that the structural history of the Beaverlodge area can be divided into four main events, as follows:

1. Regional horizontal compression (first period of deformation).
2. Regional epeirogenic movements.
3. Localized horizontal compression (second period of deformation).
4. Localized epeirogenic movements.

The block diagrams shown in Figure 6 illustrate the manner in which the Beaverlodge area appears to have responded to these four stages of tectonic activity. Each stage is discussed briefly below in chronological order. A summary of events is presented in Table 1.

1. Regional Horizontal Compression: During early Precambrian time, the initial period of crustal shortening deformed the Tazin sediments into a

TABLE 1

Time	Tectonic history	Probable type of forces involved
	tectonic quiescence and erosion to Recent	
Proterozoic	4. *Localized Epeirogenic Movements* —normal faulting —hydrothermal alteration and pitchblende mineralization related to normal faults	Localized, intense vertical forces. Tensional environment
	3. *Localized Horizontal* (2nd period of deformation) *Compression* —Athabasca rocks in Beaverlodge area synclinally folded —Tazin rocks re-folded	Horizontal compression exerted northwest-southeast. More localized and less intense than in 1
Keweenawan (?)	2. *Regional Epeirogenic Movements* —uplift in north —subsidence in south —deposition of Athabasca series with accompanying volcanic activity	Vertical crustal adjustments over a large part of the western Canadian Shield, probably caused by vertical forces, but horizontal compression could be important
	Erosion interval	
?	1. *Regional Horizontal* (1st period of deformation) *Compression* —Tazin rocks folded, granitized and metamorphosed —crushing and mylonitization of Tazin rocks during reactivation of stresses —cross-folding	Long-continued northwest-southeast compression over much of western part of Canadian Shield. Late change in direction of force suggested by cross-folding

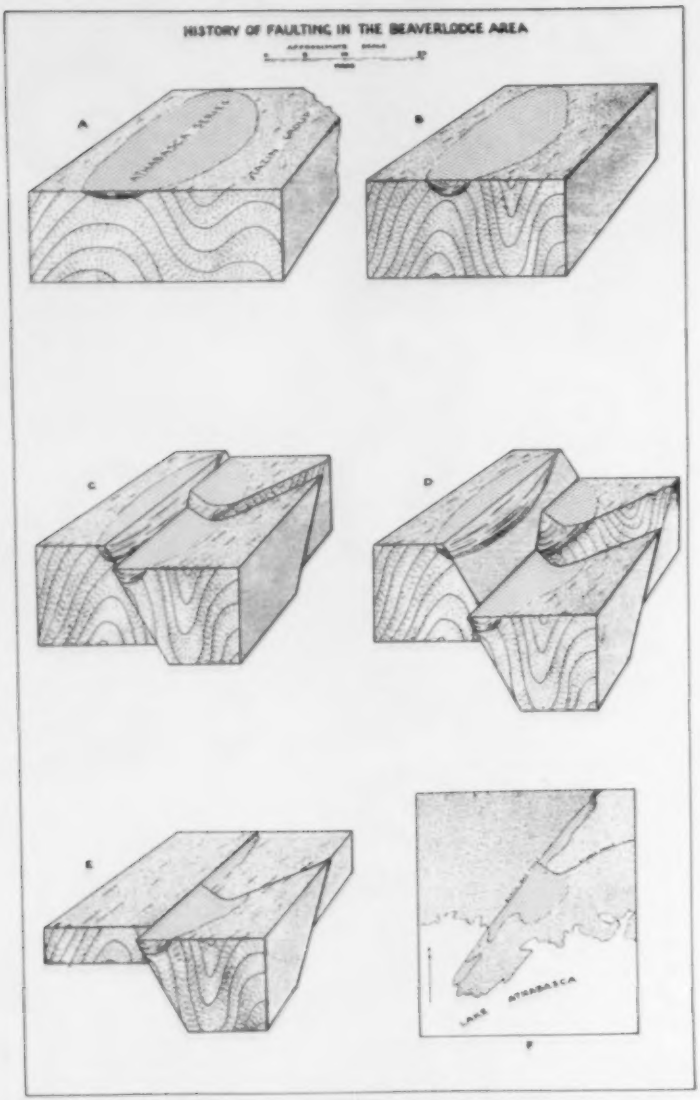
HISTORY OF FAULTING IN THE BEAVERLODGE AREA
A
B
C
D
E
F
LAKE ATHABASCA

FIG. 6.

series of northeast-trending folds. Deformation was accompanied by low-grade regional metamorphism and the formation of extensive zones of granitic rock. Subsequent compression resulted in the formation of local belts of breccia or mylonite without development of through-going faults.

2. Regional Epeirogenic Movements: Epeirogenic movements took place over much of the Canadian Shield during Proterozoic (Keweenawan?) time. The region north of Lake Athabasca was uplifted and became the source area for a great bulk of the clastic material comprising the Athabasca series. This material was rapidly deposited over a vast region of subsidence south of Lake Athabasca. Within the Beaverlodge area, the Athabasca sediments were deposited with accompanying extrusion of basaltic flows in a restricted basin that is diagrammatically illustrated in Figure 6A. This diagram also suggests the probable degree of folding of the Tazin rocks during the first period of horizontal compression, already described.

3. Localized Horizontal Compression: The second period of crustal shortening involved both the Athabasca and Tazin rocks within the Beaverlodge area. The Tazin rocks were re-folded while the Athabasca rocks were synclinally folded into an elongated trough, as shown in Figure 6B. The Athabasca rocks are completely unmetamorphosed, indicating that little or no regional metamorphism took place during this period. South of Lake Athabasca, the Athabasca series is relatively flat-lying, suggesting that the second period of compression was largely restricted to the area north of the lake. Evidence thus points to the fact that the second period of horizontal compression was less extensive, as well as less intense, than the first.

4. Localized Epeirogenic Movements: Finally, normal faults developed within the Beaverlodge area as a result of vertical crustal adjustments. Normal components of movement measurable in miles testify to the intensity of the forces involved. Figure 6C shows the initial development of the Black Bay and St. Louis-ABC faults, while Figure 6D shows their probable ultimate development. Figure 6E illustrates the area planed off to the level of the lowest block, much as it is at present. Figure 6F is a generalized geologic map of the same area, inserted for comparative purposes.

Hydrothermal alteration and pitchblende mineralization are spacially related to the faulting but are later in time than any observed tectonic features in the area.

ACKNOWLEDGMENTS

This paper is a condensation of the chapter of the writer's Ph.D. thesis that deals with the tectonic history of the Beaverlodge area preparatory to discussing the structural control of the pitchblende orebodies along the St. Louis-ABC fault. The writer is grateful to members of the geological staff of Eldorado Mining and Refining Limited. Special thanks are due to D. D. Campbell, former Chief Geologist and L. T. Jory, Chief Geologist of the Crown Company for encouragement and assistance during the period of field-work from 1955 to 1957. The writer is also indebted to Professor H. E. McKinstry

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July 1, 1958

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PRIMARY BORATES IN PLAYA DEPOSITS: MINERALS OF HIGH HYDRATION [1]

SIEGFRIED MUESSIG

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ABSTRACT

The primary borate minerals in nonmarine bedded borate deposits—those of the playa type, and their deformed derivatives—are the high hydrates. Both field and laboratory data indicate that the high hydrates are the borate minerals that form stable phases at the lowest temperatures: under the surface conditions of playas.

From a study of hand specimens of borate minerals from the new Turkish borate deposits, Meixner (18) suggested that the borate minerals having the lowest specific gravity, and hence, highest water content, are the primary minerals.

The role of temperature in the formation of the hydrous borates is shown by solid phases in the system $Na_2B_4O_7$-H_2O (19). As temperature increases, hydration of the solid phase decreases successively from borax ($10H_2O$) through tincalconite ($5H_2O$), kernite ($4H_2O$), to metakernite ($2H_2O$). This suggests that in the temperature ranges considered in the present paper—those of playas—the high hydrate (borax) is the one most likely to form as the primary mineral in nature. Studies of the Ca, Mg, and Ca-Na hydrous borate systems (14) suggest that the same statement holds in these systems.

Until recently, only borax and ulexite ($Na_2O \cdot 2CaO \cdot 5B_2O_3 \cdot 16H_2O$) have been known as primary minerals of playa deposits. However, inderite ($2MgO \cdot 3B_2O_3 \cdot 15H_2O$) has recently been found as a primary mineral in Argentina and primary inyoite ($2CaO \cdot 3B_2O_3 \cdot 13H_2O$) has been found in Peru. These four minerals are the high hydrates of their respective mineral series. None of the lower hydrates are known as primary minerals in nonmarine bedded deposits.

On burial and deformation of the primary minerals, the changes in temperatures and pressures are almost certainly in such a direction as to

[1] Publication authorized by the Director, U. S. Geological Survey.

encourage minerals of higher density and lower hydration to become stable phases. Field evidence bears this out: in all deformed deposits, secondary minerals of low hydration are quantitatively important.

THE PROBLEM

UNTIL recently, only borax and ulexite have been considered as primary minerals [2] of some of the nonmarine bedded borate deposits—those of the playa type and their deformed derivatives; these two minerals are the common minerals of the borate playas (the "borax marshes" of California, Oregon, and Nevada or the *salares* of South America). These minerals, the high hydrates of the sodium borate and of the sodium-calcium borate series, have been considered primary (and presumably syngenetic) by nearly all earlier workers. Recently, field evidence has been found (20, 22) to indicate that the high hydrate in the calcium borate series, inyoite, and the high hydrate in the magnesium borate series, inderite, are the primary minerals in their series. In each of four principal borate mineral groups, therefore, the highest hydrate appears to be the primary mineral of that group (Table 1).

A question immediately arises, of course, as to the criteria by which borate minerals of a playa can be recognized as primary. I offer the following criteria: (1) The minerals occur at or near the surface in playa muds. (2) The minerals are restricted to thin stratigraphic zones within the muds; in other words, they are in layers as if bedded. (3) The minerals occur in the muds with their own crystal habit, and as far as I know they have not been found pseudomorphous after other borates, nor have relicts of other borates been found in them. The crystallization process of salts in the muds of playas and the formation of playa salt layers are a "strictly surface phenomenon" (7). The borate minerals, other than those in crusts (with which I am not concerned here), probably form by growing *in* the playa muds. They are therefore epigenetic in a strict sense, but for all practical purposes such growth can be considered syngenetic, and I use the term in that sense.

But although the primary borate mineral in any one series appears to be the high hydrate, the high hydrates are not necessarily primary; they also occur as secondary minerals. Laboratory data indicate that the high hydrates are the lowest temperature minerals of their groups, and should therefore be the ones that form under surface or near-surface conditions—as primary minerals in playa deposits.

EVIDENCE AND REASONING

In a study of mineral specimens from the new Turkish borate deposits, Meixner (18) found that masses of colemanite and meyerhofferite have druses and other cavities, whereas inyoite, ulexite, and tertschite (15, 16) are massive or in crystal form. Therefore, it seemed to him that colemanite and meyerhofferite were formed from borate minerals of greater volume and lower density, and thus of higher water content.[3]

[2] "Primary minerals" used in the following sense: those minerals first formed, essentially contemporaneously with the enclosing sediments.

[3] Some of the water in some borates is in the form of OH groups. For example, colemanite, $2CaO \cdot 3B_2O_3 \cdot 5H_2O$, and meyerhofferite, $2CaO \cdot 3B_2O_3 \cdot 7H_2O$, should really be written $CaB_2O_4(OH)_2 \cdot H_2O$ and $CaB_2O_4(OH)_4 \cdot H_2O$, respectively (3, 4). Colemanite has the higher density, but has the same H_2O per Ca as meyerhofferite.

TABLE 1

THE PRIMARY BORATES (UNDERLINED) DISCUSSED IN THIS PAPER, AND THEIR LESS HYDROUS ANALOGUES

Mineral	Specific gravity	Composition
	COLEMANITE SERIES	
Inyoite	1.87	$2CaO \cdot 3B_2O_3 \cdot 13H_2O$
Myerhofferite	2.12	$2CaO \cdot 3B_2O_3 \cdot 7H_2O$
Colemanite	2.42	$2CaO \cdot 3B_2O_3 \cdot 5H_2O$
	ULEXITE SERIES	
Ulexite	1.95	$Na_2O \cdot 2CaO \cdot 5B_2O_3 \cdot 16H_2O$
Probertite	2.14	$Na_2O \cdot 2CaO \cdot 5B_2O_3 \cdot 10H_2O$
	BORAX SERIES	
Borax	1.71	$Na_2O \cdot 2B_2O_3 \cdot 10H_2O$
Tincalconite	1.88	$Na_2O \cdot 2B_2O_3 \cdot 5H_2O$
Kernite	1.91	$Na_2O \cdot 2B_2O_3 \cdot 4H_2O$
	INDERITE SERIES	
Inderite	1.86	$2MgO \cdot 3B_2O_3 \cdot 15H_2O$
Lesserite	1.78	$2MgO \cdot 3B_2O_3 \cdot 15H_2O$
Kurnakovite	1.85	$2MgO \cdot 3B_2O_3 \cdot 13H_2O$

Regarding the minerals of the colemanite series, Meixner (18) says: "Inyoite belongs to those minerals that crystallize first in borate deposits, whereas the more water-poor * * * meyerhofferite and colemanite are at least partly formed from it by rearrangement through dehydration and recrystallization." (Present writer's translation.) Colemanite and meyerhofferite pseudomorphs after inyoite are cited as evidence for the dehydration and recrystallization. Further: "The ulexite [shows] no cavities, and ulexite, like inyoite and tertschite, is apparently to be considered as a primary, water-rich borate of lower density, which is suited for rearrangement."

Considered by itself this evidence would not be compelling because cavities and druses can result from the solution of pre-existing minerals, and the pseudomorphs after inyoite only show that the pseudomorphous minerals are later than the inyoite; they do not show the inyoite to be primary.

The role that temperature must play in the formation of the hydrous borate minerals is shown by phase studies. In the well-studied borate system, $Na_2B_4O_7$-H_2O, Menzel and Schulz (19) show that as temperatures increase, the hydration of the solid phase decreases successively from borax ($10H_2O$) through tincalconite ($5H_2O$, but metastable), kernite ($4H_2O$), to metakernite ($2H_2O$). This suggests that in the temperature ranges considered in the present paper—those generally obtaining at or near the surface of playas—the high hydrate (borax) is the one most likely to form as the primary mineral in nature.

Studies of the Ca, Mg, and Ca-Na hydrous borate systems (from a review, 14) suggest that the same statement probably holds in these systems also. The CaO-B_2O_3-H_2O system has been most recently studied by Nikolaev and Chelishcheva at 25° C. They found the following solid phases:

$Ca(OH)_2$, H_3BO_3 (boric acid), $CaO \cdot B_2O_3 \cdot 6H_2O$, $CaO \cdot 3B_2O_3 \cdot 4H_2O$, and $2CaO \cdot 3B_2O_3 \cdot 4H_2O$, and $2CaO \cdot 3B_2O_3 \cdot 13H_2O$; the last-named compound is the mineral inyoite, the high hydrate of its series. At 30° C, Sborgi found $2CaO \cdot 3B_2O_3 \cdot 9H_2O$, a less hydrous analogue of inyoite and not found as a mineral. In the MgO-B_2O_3-H_2O systems at 25° C, $2MgO \cdot 3B_2O_3 \cdot 15H_2O$, inderite, the high hydrate of its series, is the only solid phase that occurs as a mineral among those considered here (Table 1). In the quaternary system Na_2O-CaO-B_2O_3-H_2O, studied at 25° C by Kurnakova and Nikolaev, boric acid, inyoite, borax, and ulexite are the only solid phases that also occur as minerals; the last three named are the high hydrates of their series. Boric acid occurs in many places as the mineral sassolite, but is not being considered here.

These data and deductions are supported by the mode of occurrence of the several borate minerals in playas and in their deformed derivatives.

Colemanite Series.—Colemanite, the low hydrate of its series, probably is everywhere a secondary mineral. Moreover, in an important paper on the genesis of colemanite, Foshag (6), after discussing the chemical and physical conditions existing in playas, concluded that neither colemanite nor "any simple calcium borate" will form in them. Colemanite has been reported from Salar Cauchari, Argentina, (2), but more recent work in the same area by Ahlfeld and Angelelli (1) and the writer suggests that the reported occurrence came not from the *salar* but rather from the folded bedrock deposits in the same area. So far as I know, colemanite has not been verified as a primary mineral of a playa deposit.

Meyerhofferite is not known from playas, and in occurrences in Turkey (18) and in Death Valley it is secondary.

Inyoite, at the type locality (26), occurs as pseudorhombohedrons that are largely altered to meyerhofferite. The crystals are found in druses in colemanite and are later than the colemanite, which is secondary. The inyoite reported from New Brunswick (25) occurs in marine gypsum as crystals, in veinlets, and in vugs; it is probably secondary. Inyoite is also reported from Argentina (1), but nothing is said about its manner of occurrence. The inyoite at the deposits in Turkey may or may not be primary. The inyoite of the Inder deposits is secondary (12).

Inyoite also occurs in the recent borate playa, Laguna Salinas, Peru. The mineral occurs there as a thin compact layer of crystal aggregates in mud about a meter below the surface of the playa (22). At the Peruvian playa the mineral is evidently primary. Inyoite is the only mineral of the colemanite series thought to be a primary mineral; it is the high hydrate of the series.

Borax Series.—Kernite, the low hydrate of the borax series, occurs only as a secondary mineral, in only two places, the Kramer district, California (27), and Tincalayu, Argentina (1, 20). In both these places kernite is probably the dehydration product of the primary borax, the dehydration having taken place at temperatures above those at which borax is stable.

Tincalconite is the common dehydration product of borax. It is a secondary mineral in all its reported occurrences in the bedded borate deposits. At Searles Lake, California, it occurs as euhedral crystals in fine-grained

white salts (23) and also as coarsely crystalline crusts on large borax crystals. All the tincalconite crystals "enclose sharp octahedrons of northupite" ($MgCO_3 \cdot Na_2CO_3 \cdot NaCl$) (23), and some of them have included gaylussite ($Na_2CO_3 \cdot CaCO_3 \cdot 5H_2O$). It is not known if the euhedral tincalconite crystals are primary, or are the result of recrystallization within the salt body, as the tincalconite crusts on the borax crystals probably are. In any event, this occurrence is a special case, as the Searles Lake polymineralic crystal body with its complex brines is far different from the mineralogically more simple bedded playa deposits.

Borax is known as a primary mineral from Tibet, Borax Lake, California (13), Turilari, Argentina (21), and other playas, as well as from the older deformed bedded deposits in the Kramer district, California (11, 27), and Tincalayu, Argentina (20). It is the high hydrate of its series.

Ulexite Series.—Ulexite, the high hydrate of its series, is the most widespread of all the borates. It occurs as a primary mineral in all the borate *salares* of South America and in most of the playas ("borax marshes") of Nevada and California. It also occurs as a secondary mineral in veins in the Kramer district and in many other places.

Probertite, the lower hydrate, is known only as a secondary mineral at the type locality, the Kramer district (27). That at Ryan, California, is probably also secondary (8). Both Eakle (5) and Foshag thought that the formation of probertite, rather than ulexite, calls for higher temperatures (Eakle) or higher pressures (Foshag), and therefore probertite would not form under normal surface conditions.

Inderite Series.—Inderite, the high hydrate of its series, has been found in the Inder borate district [4] in Russia (12), the Kramer district in California (9), and at Tincalayu, Argentina (20). At the Argentine locality, the mineral probably is primary and probably formed in a playa. At the type locality in Russia it is secondary (12). In the Kramer district, inderite occurs with its polymorph, lesserite, and both minerals are probably secondary, but "both minerals were formed at temperatures and pressures not far above ordinary" (10).

Kurnakovite, the lower hydrate of the series, is known only from the Inder deposits (24), where it is partly associated with szaibelyite (ascharite). Judging from an earlier description of the deposits (12), it is probable that kurnakovite is a secondary mineral at this locality.

Other Hydrous Borates.—Other common borates of nonmarine bedded deposits include priceite ($4CaO \cdot 5B_2O_3 \cdot 7H_2O$) and hydroboracite ($CaO \cdot MgO \cdot 3B_2O_3 \cdot 6H_2O$) and their more hydrous analogues. Priceite (pandermite) is the ore mineral of some deposits in Turkey, and Schlüter (28) concludes that some of it is primary; Meixner (18) thinks otherwise. In Death Valley, especially at Monte Blanco, priceite forms extensive secondary veins.

Tertschite ($4CaO \cdot 5B_2O_3 \cdot 20\text{–}21H_2O$; 15, 16), the higher hydrate of priceite, is reported to be a primary mineral (18), but the data are inconclusive.

[4] The Inder borate deposits are not playa deposits (12). Mention of the deposits and minerals from them is made here only because minerals from them also occur in playa deposits or in their deformed derivatives.

Most of the literature about the occurrences of hydroboracite and the higher hydrate, inderborite ($CaO \cdot MgO \cdot 3B_2O_3 \cdot 11H_2O$) is in Russian and not available to me. In one Russian reference (12), hydroboracite is given as a secondary mineral. Hydroboracite is reported at Pastos Grandes, Argentina (1, 2), in deformed nonmarine sediments, but nothing is said of the manner in which it occurs.

SUMMARY

Until recently, only borax and ulexite had been known as primary borate minerals, and the allusions in the literature that the high hydrates ought to form under surface conditions had only tentative geologic support. In 1957, however, inderite was reported (20) as most probably being a primary mineral in Argentina, and inyoite is now reported (22) as a primary mineral in a Peruvian playa. In borate deposits of the playa type, therefore, the known primary minerals are the high hydrates. Data from phase studies are corroborative evidence that the primary minerals *should* be high hydrates because they are the ones that form stable phases at the lowest temperatures, or under the surface conditions of playas.

On burial and deformation of the primary minerals, the changes in temperature and pressure are almost certainly in such a direction as to encourage minerals of higher density and lower hydration to become stable phases. Indeed, the field evidence seems to bear this out: in all the deformed bedded deposits, secondary minerals of low hydration are quantitatively important—they form borate ore.

ACKNOWLEDGMENTS

For several years I was a member of a U. S. Geological Survey project engaged in the study of borate deposits of the western states under the supervision of Ward C. Smith. The project was supported in part by funds from the Bureau of Aeronautics, U. S. Navy. Many of the ideas expressed here had their inception or were further developed in discussion with my colleagues on this project, and I acknowledge my indebtedness to them.

NOTE

After this paper was in page proof, Dr. W. T. Schaller kindly wrote me that lesserite (Table 1) is identical with inderite and is not a new mineral. See: D'Ans, Jean, and Behrendt, Karl-Heinz, 1957, Über die Existenzbedingungen einiger Magnesiumborate: Kali u. Steinsalz, v. 2, pt. 4, p. 121. Probably the specific gravity of inderite should be that of "lesserite" (1.78) rather than being 1.86.

U. S. Geological Survey,
Spokane 4, Washington,
Sept. 3, 1958

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SCIENTIFIC COMMUNICATIONS

NOTES ON THE JOINT FIELD CONFERENCE OF THE NEW MEXICO AND THE ARIZONA GEOLOGICAL SOCIETIES

The Ninth Annual Field Conference of New Mexico Geological Society was held with the cooperation of the Arizona Geological Society in the Black Mesa Basin area of northeast Arizona, October 16–18, 1958. Three hundred and forty persons attended in a caravan of 110 vehicles.

The Guidebook [1] was edited by Roger Y. Anderson, University of New Mexico, and John W. Harshbarger, U. S. Geological Survey. The papers listed below cover a wide range of subjects:

Nomenclature chart of the Four Corners Area	G. K. Elias
Precambrian rocks of northern Arizona	J. F. Lance
Devonian system of the Black Mesa basin	D. S. Turner
The Redwall limestone	E. D. McKee
Pennsylvanian paleogeography of Arizona	Kay Havenor and W. D. Pye
Permian sedimentary rocks of the Black Mesa basin area	H. W. Pierce
Moenkopi and Chinle formations of the Black Mesa and adjacent areas	J. P. Akers, M. E. Cooley, C. A. Repenning
The Shinarump member of the Chinle formation	C. G. Evensen
Stratigraphy of the uppermost Triassic and the Jurassic rocks of the Navajo country	J. W. Harshbarger, C. A. Repenning, J. H. Irwin
Late Cretaceous stratigraphy of Black Mesa, Navajo and Hopi Indian Reservations, Arizona	H. G. Page, C. A. Repenning
Tertiary stratigraphy of the Navajo country	C. A. Repenning, J. F. Lance, J. H. Irwin
Catalogue of stratigraphic names of the Black Mesa basin and adjacent areas	D. S. Turner
Tectonics of the Black Mesa basin region of Arizona	V. C. Kelley
Generalized tectonic map of the Black Mesa Basin	W. W. Doeringsfeld, C. L. Amuedo, J. B. Ivey
Physiography of Black Mesa basin area, Arizona	M. E. Cooley
The Pleistocene glaciation of San Francisco Mountain, Arizona	R. P. Sharp
Oil and gas potentialities of northern Arizona	S. C. Brown, R. E. Lauth
Helium in southern Black Mesa basin	E. C. Beaumont
Uranium deposits in northern Arizona	H. S. Birdseye
Uranium mineralization near Cameron, Arizona	E. M. Bollin, P. F. Kerr
Summary of coal resources of the Black Mesa coal field, Arizona	R. B. O'Sullivan

[1] Available, $8.75 postpaid, from the New Mexico Bureau of Mines and Mineral Resources, Socorro, New Mexico.

Ground water in Black Mesa basin and adjacent areas.....J. P. Akers
J. W. Harshbarger
The Gallup sandstone as a fresh water aquifer.....S. W. West
The geology and dating of Sunset Crater, Flagstaff, Arizona.....T. L. Smiley
Some geologic features of the St. Michaels area, Arizona.....R. L. DuBois
Sandstone cylinders as possible guides to paleomovement of ground water..D. A. Phoenix
Land tenure in northeastern Arizona.....T. W. Cabeen
Life zones in northeastern Arizona.....R. Y. Anderson

More stress was laid on the stratigraphic and structural features than on the economic aspects but this is natural since the area has become important economically only within the past few years, particularly as the result of finding uranium, natural gas, and petroleum on the Navajo Indian lands in the extreme northeast part of the area.

The trip started from Gallup, proceeded to Window Rock, the center of Navajo Indian Government, across the Defiance Uplift via Hunters Point, Lupton, and Sanders, to the Petrified Forest, then to Holbrook, Keams Canyon, Oraibi, and Flagstaff, and from Flagstaff to Echo Cliffs at the Gap, then to the Grand Canyon.

The trip included such features as the Permian beds resting on Precambrian rocks at Hunters Point on the Defiance Uplift; the geologic section at Lupton where the Kayenta formation is topped by the Cow Springs-Entrada sandstone (once considered to be Navajo though no true Navajo occurs in this section). Also, the Wingate sandstone below the Kayenta beds is now placed in the Triassic instead of Jurassic. A visit was made to a non-swelling montmorillonite deposit near Sanders, Arizona, for which nearly 5,000,000 tons of clay had been shipped to oil refineries for use as a catalyst and as a bleaching agent.

The Petrified Forest, with its massive agatized logs found in the shales of the Petrified Forest member of the Chinle formation, is always a fascinating spot. The museum there has some interesting dioramas and some beautiful polished logs several feet in diameter.

At a night meeting at Holbrook, Dr. Vincent Kelley discussed the tectonics of the Basin, and showed some memorable slides of the various structures and formations. The climatology of the area also was discussed by Roger Anderson.

Before reaching Keams Canyon, stops were made in the Hopi Buttes area near Indian Wells to visit two diatremes (explosive volcanic vents). At the first locality, volcanic bombs 5 to 6 feet tall and 2½ to 3½ feet in diameter occur interbedded in ash. At the second locality, the Coliseum diatreme, a vast amphitheater three-fourths mile in diameter, is enclosed by the high, partly eroded walls of the diatreme. An inner bed, a resistant fresh water limestone eight inches thick, helps to preserve the feature. The dips in the outer wall are 65° to 70°, and in the inner wall 15° to 20°. Several football games could be played simultaneously in this "bowl." Access was gained through a narrow exit cut by a small stream.

Fragments of Precambrian granite thrown out from a depth of 7,000 to 8,000 feet occur in the diatreme, which is now, however, largely filled with 600 feet of Pliocene to Recent sediments that have subsided slightly into the vent. The necks of the diatremes, where seen in the Hopi Butte area, vary

from 50 to several hundred feet in diameter but the craters made by the explosions vary from a few hundred feet to nearly a mile in diameter. Sediments in some of the diatremes supply potable water. Eugene Shoemaker of the U.S.G.S., who discussed the features, stated that the diatremes would have little or no effect on the gas and oil accumulations at depth as somewhat similar conditions exist near some of the gas and oil fields of northwest New Mexico.

At Keams Canyon, the coal seams were discussed and also the various geological formations from the Dakota to the Upper Mesaverde. There are some two billion tons of semi-bituminous coal available. An optimistic talk was given by Dan Turner on the gas and oil possibilities of the Black Mesa Basin. He stressed the relatively slight prospecting of the basin and believed gas and oil would be found in beds ranging from Devonian to upper Permian.

At the Oraibi High School, the caravan was welcomed by two officials of the Hopi tribe of Indians who discussed their tribal history and customs, and their economy.

The third day the caravan crossed the San Francisco Mountains on its way to Sunset Crater where the glaciology of San Francisco Peak was discussed. The Sunset Crater and adjoining craters, some 1,100 years old, evidenced late volcanic action. There was not time to visit the Paleozoic section exposed on the east flank of the San Francisco mountains.

Leaving Sunset Crater, the caravan proceeded to the Wupatki Indian ruins, where the early Moenkopi beds were discussed. The next stop was at the Gap where the Moenkopi beds, the Chinle beds, the Wingate sandstone, the Kayenta sandstone and shale, topped by the Navajo sandstone, 1,000 feet thick, form east-dipping beds in the tall west-facing cliffs on the Echo Cliffs monocline. Here the Navajo sandstone is seen at its thickest. The caravan then back-tracked to the south side of the Grand Canyon stopping enroute to observe Coconino Point, a sharp east- and north-dipping monocline cut by several grabens. At Grand Canyon all of the Paleozoic section was discussed from Desert View lookout by E. D. McKee who also led part of the group into the Canyon on a Kaibab Trail stratigraphic hike the following day.

In the main, the discussion dealt largely with the stratigraphy of the area, although the economic features, especially oil and water, also were discussed.

This is a vast area with coal, clays, and water yet to be developed, with several rich uranium mines, and with the gas and oil possibilities barely scratched. The money paid to the Navajo Indians from these resources is already changing the patterns of Indian life on the Reservations.

This area is one of the most colorful in America with the red, pink, and bluish colors of the Painted Desert beds, the massive reds of the Moenkopi, Wingate and Kayenta beds with the tawny to white of the Navajo sandstone standing out in great cliffs.

There was not time to take in the Canyon DeChelly and Monument Valley but the geologists will long remember the conference as one of the most interesting and fruitful they have attended. The Black Mesa Basin, too, is gaining the recognition it so richly deserves.

DORSEY HAGER

SALT LAKE CITY, UTAH,
December, 1958

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DISCUSSIONS

EN ECHELON FOLDING

Sir: Mr. J. D. Campbell presents an interesting and instructive description and analysis of an echelon folding and the resulting fold patterns, and also appositely points out the economic importance of the recognition of fold types and patterns.

In a paper in press (1) I deal with fold types and the significance in structural interpretation of their outlines or axial traces in both longitudinal projection and plan projection. The two fold types discussed are the same as those described by Campbell and have been given names that are offered as alternatives to those he uses.

The fold type illustrated in Figure 2(a) [1] and the right half of Figure 2(b) (c) and (d), is an echelon fold. This term is used because the fold consists of three components (two anticlines and one syncline as in the illustration, or two synclines and one anticline) forming a single structural unit and arranged in an en echelon pattern. An echelon fold can be associated with (1) an anticlinal structure, in which case it comprises two anticlines and a mutual or shared syncline and is known as an anticlinal echelon fold, and (2) a synclinal structure, in which case it comprises two synclines and a mutual or shared anticline and is known as a synclinal echelon fold. In addition it can be right or left hand, as described by Campbell. Thus Figure 2 shows two right hand anticlinal echelon folds. The term as defined is fully descriptive and its use does not affect or preclude the use of the term en echelon where required. The axial plan projection pattern, from which the term zig-zag is derived, is in many cases not a zig-zag one. For instance in the case of an overturned fold the axial plan projection pattern is similar to the logitudinal projection pattern for the same fold (1, Fig. 16).

A fold occurring on and confined to the flank of a syncline or anticline, such as any of those shown in Figure 3 (p. 452) is a *pod fold*. A pod fold consists of an anticline and a syncline with a mutual or shared limb; plunge, dimensions, shape, and rate of development may vary within wide limits. These folds are described by Campbell as having pointed elliptical outlines (p. 453), and subsequently as having elliptical patterns or as elliptical folds (p. 465 et seq.) Ellipses are familiar shapes, well known and used in structural geology, and the forms or patterns illustrated are not true ellipses; in nature, too, the patterns vary considerably from the ideal regular shape, so that the final shape may be far from the ellipse. The term pod is simple, readily visualized, descriptive of the shape of the fold itself and its pattern or

[1] All figures and page numbers quoted refer to Campbell's paper unless otherwise indicated.

outline in plan or longitudinal projection, and at the same time does not imply a regular or precise shape. With apologies to Mr. Campbell, the proposed terms will be used in this discussion. The presence of only these two types of fold in widely spaced areas in Australia and Africa suggests strongly that echelon and pod folds are in fact the basic fold forms and that all folds are some combination, modification, or development of them.

En echelon folding is recognized by Campbell, Willis (2, p. 95), and others as being due to the action of a minor force or stress oblique to the main one causing the folding. However, both pod and echelon folds can and do develop where there is no evidence of any oblique stress during folding.

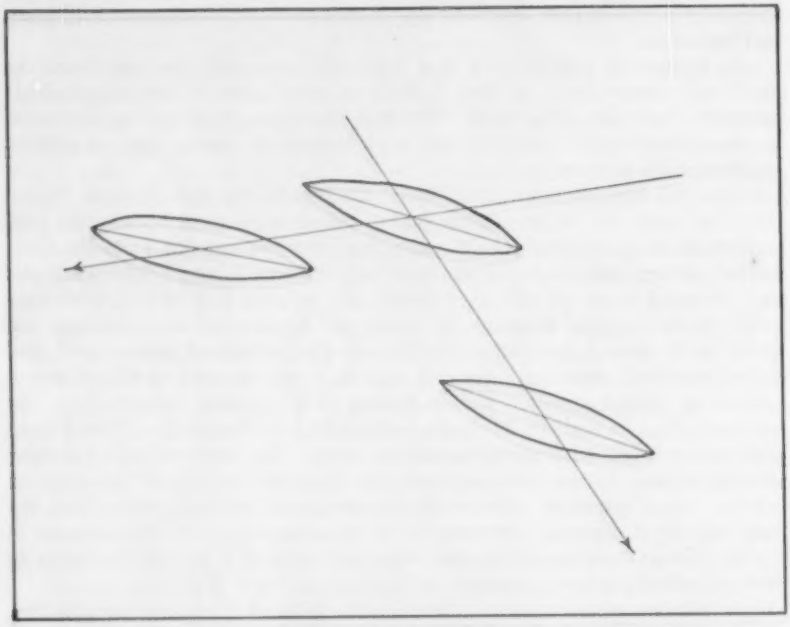

FIG. 1.

This is the case on the Roan Antelope, Northern Rhodesia, where both echelon and pod folds occur in profusion, the former being more common. They are arranged haphazardly relative to the regional axis of folding, with plunges ranging up to 90° from the latter, though axial planes are approximately parallel.

Therefore the main, if not the only, effect of the forces described and analyzed by Campbell (pp. 448–9, Fig. 1) is not their development, but *the en echelon arrangement of the folds* (*Fig. 3*). This indicates that the Roan type of folding is the general case, while the en echelon arrangement is a particular variation of the general case due to the presence of a particular set

of conditions. For this reason Campbell's conclusions regarding the relationship of pod and echelon folds to the regional structure or the overall plunge of a fold structure cannot be of general application. In this regard the writer is in full agreement with the statement (p. 472) that "an extensive three-dimensional knowledge is needed before the existence and characteristics of an en echelon pattern can be recognized."

The danger involved in attempting to apply the conclusions without adequate knowledge, or accepting only a pair of en echelon folds as indicating the overall plunge, is shown in the following hypothetical example, illustrated in Figure 1. This is a case where there are three pod folds with approximately the same plunge, on the same limb of a large fold, arranged haphazardly but so as to give about the same amount of shortening of the limb in the portion under discussion. It is clear that completely different overall plunges could be derived by joining the two possible combinations of pairs of "en echelon" pod folds and there is nothing to indicate whether either is associated with the correct overall plunge. Although such pod folds would commonly have different plunges indicating that they are not part of a true en echelon series, there is no reason why two adjacent folds should not have somewhat similar plunges, and such a condition has been observed. Thus, any two pod folds found on the flank of a larger fold will be offset from each other, but they are not necessarily part of an en echelon series.

The establishment of an en echelon pattern is a rather difficult task, but the presence and often the nature of echelon and pod folds is more readily detected, and their delineation should be the first step in structural interpretations. For instance, the Birthday anticline, Birthday Gift Mine, Burbanks (pp. 453–4, Fig. 4) consists of two linked anticlinal (right hand) echelon folds—A1-S2-A2 and A2-S5-A5.

There are inconsistencies in the presentation and application of the geology of the Kalgoorlie area (pp. 455–9, Figs. 5, 6, 9) no doubt due in part to the fact that the illustrations "gloss over many features of a complex fold and fault pattern." In longitudinal projection a synclinal axial (trough) trace cannot lie at a higher elevation than the adjacent connected or related anticlinal axial (crest) trace—where the two meet the fold terminates and so do the traces. The crossing of trough and crest traces in Figure 6(b) indicates that the Paringa-Brownhill fold is not a simple pod fold but some combination of pod and echelon folds, and that the Lake View Australia fold in the south is not a pod fold at all, but a complex combination. A further difficulty in Figure 6 is that the axial traces of the Brownhill syncline and the Paringa anticline meet in the southern portion of the plan projection (a), but in the longitudinal projection (b) they are left open; the same applies to the axial traces of the Australia syncline and the Lake View anticline in the north. The axial traces of a pair of folds must behave consistently in both plan and longitudinal projections, i.e., they must join in both or not join in both, or either the drawing or the interpretation of the folding is incorrect.

The somewhat arbitrary joining of the estimated "centres" of what could, from the illustrations, be one pod fold and one pod-echelon fold complex, two sets of echelon folds, or two pod-echelon fold complexes, to obtain

the overall plunge of 24° cannot be justified by the information given. It is also far from clear how the 17° plunge of the Kalgoorlie anticline (p. 459) gives a check on this overall plunge of 24°. The 17° is in fact closer in magnitude to the average plunge of the folds on Figure 6(b), which have an average plunge of 12° to 15° as measured. This would appear to suggest rather that the folds all plunge at approximately the same angle, and that this angle might possibly be the regional or overall plunge.

In Figure 9(b) the "pod" folds formed by (1) the Paringa anticline and the Brownhill syncline and (2) the Lake View anticline and the Australia syncline, are shown to have plunges of 5° instead of the 12° to 15° in Figure 6 (b). The inferred folds of Figure 9(c) are therefore apparently based on an assumed overall plunge of 24° that cannot be justified, and a minor fold plunge nearly 10° different to that previously given! For instance, if an average plunge of say 14° is used for the minor pod folds and the overall plunge of 24° is accepted, the plunge of the west side pod folds of Figure 9(c) should be 34°, whereas we are told (p. 463) that the plunge on the west side of the field is more than 40°.

There is a transposition of the terms flatter and steeper in the abbreviated rule at the bottom of page 459, which should read:

Left, right or right, left—Individuals flatter.
Left, left or right, right—Individuals steeper.

Campbell makes out a convincing case for the type of folds to be expected from the combination of pod and echelon folds, and the writer has seen at least one pod fold with two minor echelon folds, one anticlinal and one synclinal, very similar to those shown in Figure 12. However there are in the same area echelon folds as large as the above pod fold with small pod folds on their flanks, so that it would appear that there are a number of possible combinations of the two types of fold.

The statement (p. 465) regarding the size of folds is in general correct in that both echelon and pod folds could, and undoubtedly do, occur through a wide size range, from major regional structures to small minor folds. The case of drag folds is however considered to be rather different. The term drag fold has frequently been used to describe small folds associated with larger ones. A true drag fold, however is understood to be one due to relative drag or slippage between beds or laminae during folding.

Ordinary folds have their general nature decided at an early stage of the folding, when they appear as gentle undulations. These will not change in basic form, but will merely become accentuated or distorted as they develop into folds. This is well illustrated by Willis (2, p. 106, Fig. 49a) in the drawing of a gently folded specimen; gentle folds or warps that will develop into pod and echelon folds can be observed. Similarly, Cluver (3) illustrates gentle but less clearly delineated folds in the East Rand basin of the Witwatersrand System (3, p. 113, Plate II). Drag folds are caused by the relative drag or slippage between layers as these folds develop. They are mostly of small scale, affecting mainly the laminae of incompetent beds, and are probably more prevalent near fold axes. There does not appear to be

any reason why they should not form on a larger scale under suitable but probably rare conditions. There could be confusion between such larger drag folds and minor folds.

In any fold, bedding slip and therefore drag takes place along and between the beds in a plane perpendicular to the axis of the fold. Drag folds due to this movement will form with their axes perpendicular to this plane, i.e., parallel to the axis of the fold in which they occur. In the case of an en echelon arrangement of minor pod folds, the drag folds will be affected by the lateral movement caused by the oblique stress prevalent in this type of folding. The interaction of this movement and the main movement causing the folding would result in the drag folds being "swung" off the direction of the main fold axis and possibly also result in an en echelon arrangement of the drag folds. In the vicinity of a minor en echelon pod fold the lateral or oblique movement affecting the pod fold and the drag folds is the same, and there is therefore every reason to suppose that the drag folds will be swung or deflected the same amount as the pod fold. This leads to the conclusion that the drag folds near any en echelon pod fold will have the same orientation as the pod fold at its nearest point, i.e., the drag folds are always parallel to the axis of the fold in which they occur. Near the axial plane of the main fold drag folds are parallel to the axis of that fold. A more detailed description and analysis of the orientation of rock fabric and lineations is given in (1). Lineations formed by the intersection of bedding and axial plane cleavage are commonly associated with drag folding. Near axial planes these lineations and therefore the drag folds are parallel to the axes of the folds in which they occur.

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LUANSHYA,
N. RHODESIA,
Dec. 16, 1958

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THE NAIRNE PYRITIC FORMATION, AUSTRALIA

Sir: The article by Brian J. Skinner about the Nairne Pyrite Formation in ECONOMIC GEOLOGY for August 1958 (p. 546–562) aroused my interest. He attempted to estimate the temperature and pressure of metamorphism in the Nairne Pyritic Formation by the combined use of the pyrite-pyrrhotite and pyrrhotite-sphalerite geologic thermometers. The results from the two methods did not agree, and Skinner feels that the pyrite-pyrrhotite temperature of 275° C was to be preferred to the 500° C (plus pressure correction) for pyrrhotite-sphalerite.

However among the minerals created by metamorphism in the Nairne Pyritic Formation are andalusite-kyanite and spessartite garnet. Andalusite (1) and presumeably kyanite have a stability range under hydrothermal synthesis from 450° C to around 650° C. Variation with pressure is probably small (experimental pressures 10,000–30,000 psi). Iron-manganese garnets (2) have been prepared under hydrothermal conditions below 700° C, at pressures below 114,000 psi (8,000 kg per sq cm). With two other factors pointing toward temperatures around 500° C instead of 275° C, further experimental work on the pyrite-pyrrhotite geologic thermometer would be desirable. Skinner thought that a high manganese content might invalidate the pyrrhotite sphalerite geologic thermometer. However high manganese content (3) is an additional indication of a high temperature of formation.

The geothermal gradient of 20° C per km used by Skinner with depths of burial of 26,000 to 50,000 feet does not give temperatures exceeding the minimum temperature for the formation of andalusite-kyanite. However by using a figure of 35° C per km or approximately 1° C per 100 ft (North American Average) temperatures approximately as high as needed are obtained (260–500° C).

Indications are that critical surveys of the data on the formation of certain minerals combined with review of field work should fix the temperature and pressure during metamorphism of the Nairne Pyritic Formation within fairly narrow ranges. As an obvious example the formation apparently was not subjected to temperatures and pressures required for spessartite except locally or spessartite garnet would probably be more plentiful.

The composition of the plagioclase ($Ab_{63}An_{33}Or_4$ by partial analysis) in the Nairne Pyritic Formation is coupled with a pyrrhotite-sphalerite temperature of 500° C (plus pressure correction). The composition of plagioclase changes from nearly pure albite in lower grades of metamorphism to more calcic plagioclase with increasing metamorphism (4).

The temperature indicated agrees in magnitude with the estimated boundary temperature of 450–500° C (Turner and Verhoogan) between the facies epidote-amphibolite and amphibolite. In both facies andalusite-kyanite and muscovite-microcline would be stable pairs. Epidote-amphibolite would normally have oligoclase as the plagioclase feldspar, while amphibolite has more calcic plagioclase. $Ab_{63}An_{33}Or_4$ is in the andesine range and apparently is the plagioclase feldspar found at temperatures over 500° C during metamorphism when Zoisite is not present.

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January 6, 1959

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ON THORIUM-URANIUM RATIOS IN CONGLOMERATES AND ASSOCIATED ROCKS NEAR BLIND RIVER, ONTARIO

Sir: Gerald M. Friedman discusses (vol. 53, p. 889–890, Nov. 1958) thorium : uranium ratios in some conglomerates near Blind River. He refers to a paper by C. F. Davidson (vol. 52, p. 668–693, 1957) who states that Blind River conglomerates contain much more uranium than thorium, and who concludes on "geochemical" grounds that this supposed low ratio of thorium to uranium (0.3) precludes any possibility of detrital (or even syngenetic) origin for the radioactivity in these rocks and ores. Friedman, however, cites some analyses of conglomerates from one part of the district which show high ratios of thorium to uranium (3 : 1 to 13 : 1), and suggests that if Davidson's reasoning is correct the radioactivity in "at least a part of the Blind River deposits" may be of sedimentary origin.

The writer, who has spent five years studying these radioactive ores and rocks, wishes to point out that Davidson's references to a low thorium to uranium ratio are misleading. Friedman's contribution is therefore welcome, but it should not be thought that this is a new contribution either to our general knowledge of the "Blind River deposits" or to the published record.

The term *Blind River deposits*, as commonly used, is somewhat ambiguous; it is not certain whether individual authors are referring to ore deposits only or whether they mean to include other rocks as well. Radioactive quartz-pebble conglomerate beds are found here and there throughout an extensive region north of Lake Huron. They are relatively abundant near Blind River. Locally, within a certain stratigraphic unit, they are particularly thick, numerous, and highly radioactive. Large parts of these conglomeratic zones contain sufficient uranium to be considered ore. Mineral explorers have known since 1953 that the radioactivity in many occurrences of quartz pebble conglomerate is due mainly to thorium rather than uranium. It has become more and more apparent that the ore deposits near Blind River represent exceptional, uranium-rich, deposits within an extensive province of thorium-rich clastic sedimentary rocks.

R. J. Traill (1) states that some specimens contain abundant monazite and describes one specimen of monazite-rich conglomerate from Dury Township which contained about 0.26 percent ThO_2 and 0.02 percent U_3O_8, a thorium : uranium ratio of 13 : 1. The writer (2) has emphasized the ubiquitous nature of the occurrence of monazite in the radioactive conglomerates and associated clastic rocks in the area, and the fact that thorium : uranium ratios vary widely but are commonly greater than one. Roscoe and Steacy (3) in a recent paper summarize the results of hundreds of thorium and uranium analyses of rocks in the area. Within ore zones ratios vary from 0.1 to 4.0 and rocks with different ratios may be interbedded; low-grade conglomerates outside the ore zones show ratios greater than one (up to 16); most quarzites, other sedimentary rocks, and older granites have thorium : uranium ratios around 2 to 2½, but individual specimens range from as low as 0.5 to as high as 5.0. It is clear that the sedimentary rocks as a whole, and the ore-bearing

stratigraphic unit, contain considerably more thorium than uranium, principally in the mineral monazite.

S. M. Roscoe

Geological Survey of Canada,
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Dec. 23, 1958

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CORRELATION OF AEROMAGNETIC DATA WITH SOURCE MINERALOGY

Sir: We have recently encountered problems paralleling those treated so exhaustively by A. R. Balsley and A. F. Buddington (Econ. Geol., Vol. 53, No. 7). The investigation of *anomalous* negative magnetic anomalies may lie ahead, but in the extension of the Appalachian province across Newfoundland it has been found that the lack of anomalies over known ultramafic rocks presents an *anomalous* situation in itself.

The practical value of researches similar to those of Balsley and Buddington is a prime factor suggesting that they should be further encouraged and assisted. The known orebodies within the chrysotile asbestos fields of Newfoundland are in close spatial association with those magnetic anomalies created through the effect of the magnetite content of the serpentinized ultrabasic host-rocks.

It was with some surprise, and certain misgivings, that chrysotile fibers of commercial quality were discovered during 1955 and 1956 in areas of the Burlington (now known as the Baie Verte) [1] peninsula previously mapped exclusively as granite. Further work showed that the fiber-bearing veins occurred in an ultramafic, most likely an ultrabasic host-rock, exposed in limited outcrops as windows within a widespread granite sill of a maximum thickness of several hundreds of feet. Columnar jointing in this sill is only equalled in the Giant's Causeway of Northern Ireland, and this phenomenon has not previously come to my notice in a rock of approximately granitic composition.

Aeromagnetic surveys have in the past been a normal preliminary stage in the search for those ultrabasic host-rocks regarded as a prerequisite for the existence of chrysotile deposits. The occurrence of showings of fiber that give every promise of developing into commercial deposits, associated, and in fact within host-rocks giving rise to no magnetic anomaly might shatter some preconceptions concerning exploration technique as applied to asbestos.

The simple explanation in this instance is that the iron oxide present in the ultramafic rocks carrying the chrysotile is in the form of hematite ex-

[1] Formerly the Cape St. John Peninsula.

clusively. Nothing has yet been done to indicate either the primary or the secondary origin of this hematite, i.e., whether it should be considered an original constituent of the ultramafic rocks, or a product of oxidation to martite. It should perhaps be noted that no certainty exists as to the intrusive or extrusive origin of the ultramafic rocks.

The most straightforward explanation of the conditions outlined by Balsley and Buddington appears to be that where ilmenite and magnetite occur together, and where the magnetite is in significant amount, the ilmenite derives its magnetization through induction by the nearby magnetite, rather than directly from the earth's imposed field; thus is its sign the reverse of that possessed by the earth's magnetic field at the time of cooling below the Curie point.

As with similar intensive studies in other fields, the current one gives rise to more questions than it answers. Three that immediately come to mind are:

(i) what amount of magnetite is significant?
(ii) does ilmenite occur without significant magnetite?
(iii) when ilmenite occurs without significant magnetite, is its remanent magnetization of reverse polarity?

While Balsley and Buddington have been able to classify the rock types beneath negative anomalies into three distinct divisions, it may be of added interest to consider the implications of the fourth division, that represented by the neutral anomalies of the Baie Verte peninsula of Newfoundland (and, no doubt, of other localities within the Appalachian province of North America). This type of rock contains exclusively non-titaniferous hematite, no magnetite, no ilmenite, no ulvöspinel, virtually no rutile, no anatase (the TiO_2 has been determined at 0.01 percent), and with the FeO molecule present solely within the rock-forming silicates.

In Newfoundland, as the authors had assumed at the start of their studies in the Adirondack area, magnetite plays the major role in determining both positive and negative magnetic anomalies. The relative positions of each are conditioned by the shape and spatial relationships of the ultramafic rocks.

The absence of anomalies over areas underlain by ultramafic rocks has been explained purely upon the existence of the Fe_2O_3 molecule in the mineral hematite (and in the rock-forming silicates). There is thus no recourse to extraneous minerals, nor textures, to find a logical reason for the existence of these areas of neutral regional magnetism.

The authors' conclusion that "all the intermediate members of the $Fe_2O_3 - FeO \cdot TiO_2 - TiO_2$) series (now possess) reverse remanent magnetization of sufficient intensity to overcome the normally-directed induced and remanent magnetization of an equal (or greater, or less?—WJB) percentage of magnetite" leads inevitably to the conclusion that more original magnetite has been altered to martite than the quantity of original ilmenite that has become metailmenite.

Assuming that the originally induced magnetization of the ilmenite was equal to (or less) than the magnetite by which it had been induced, if the

induced magnetism now present in the remaining ilmenite is of reverse sign to the induced magnetism in the remaining magnetite (and of equal or lesser magnitude), and if the remanent magnetization is equal to or less than the original magnetization in the amount of magnetite present before martitization began, then it is clear that martitization has affected the original magnetite to a greater degree than similar and comparable alteration has affected the original ilmenite.

This statement would appear to satisfy the other conditions determined by the authors.

It is thus established that the presence of titania is essential to the existence of negative aeromagnetic anomalies for which there is no reasonable explanation upon the basis of the shape and spatial relationships of magnetite (and pyrrhotite) -bearing rocks.

We would query the use of the term *essential* in the authors' statement to the effect that pyrrhotite:

> apparently does not play an essential role in the aeromagnetic anomalies of the Adirondacks

since no further treatment is given the question thus raised. This mineral does play an essential role in any consideration of aeromagnetic data that is contemplated for mineral exploration purposes, no matter how minor, statistically speaking, may be the pyrrhotite concentrations that may become involved.

The diagrams (p. 782, *loc. cit.*) are an excellent means of summarizing the qualitative and quantitative data on the mineralogy of the systems, but they should be drawn larger, and carry much more information. At the same time, it would be useful for future researchers, to tidy up the nomenclature and avoid the overlapping that at present so patently exists. What happened to *basanomelane* (-ite?)?

The total iron appears to yield no clue as to the possible degree of magnetization for the simple reason that original magnetite may have undergone total alteration to martite. The following equations might be proposed:

martitization

$$4Fe_3O_4 + O_2 = 6Fe_2O_3$$

leucoxenization

$$12FeO \cdot TiO_2 + 3O_2 = 6Fe_2O_3 + 12\,TiO_2$$

(in $CaO \cdot TiO_2 \cdot SiO_2$ or in metailmenite)

Another possible explanation of a neutral aeromagnetic picture could be that the martitization and leucoxenization were in such delicate balance as to wipe out either the positive or the negative anomalies normally associated with a specific magnetite content in ultramafic rocks. Mineralogical investigations may well show this to have a limited application within the Newfoundland area.

Perhaps one final question: why should the total iron be greater where magnetite is also present, than where ferrian ilmenite (or martite) alone is present?

In summary, the chief differences noted in the Baie Verte peninsula of Newfoundland have been: (i) the freedom from titania; (ii) the existence of neutral anomalous conditions in the aeromagnetic coverage; (iii) the 100 percent effectiveness or totality of martitization (?) in the absence of titania: is this a decisive factor? These conditions also suggest that where magnetite was originally present, and if martitization is incomplete, some titania (in the form of ilmenite) is essential to the appearance of neutral areas and those of anomalous negative intensity such as those treated by the authors.

In conclusion it may be asked whether martite and metailmenite are necessarily unrelated to the present surface (in view of the example from the Raquette River, p. 785). In Newfoundland the wholesale martitization may have occurred in one of three ways, at any one of four occasions:

(i) during lithification in the presence of oxygenated sea-water, assuming that the ultramafics were originally submarine lavas;
(ii) during an earlier period of exposure to the atmosphere, observing concurrently that the granite sill has been intruded along an unconformity;
(iii) during the pre- or post-glacial erosion periods.

If there is no titania present, then the aeromagnetic picture suggests uniform martitization throughout the ultramafics, a situation difficult to relate to surface effects other than under (i) in the preceding paragraph. If the martitization is unrelated to conditions at the time of extrusion of the ultramafic rocks, then it must be ascribed to processes other than those of near-surface oxidation, i.e., perhaps the hematite is an original constituent?

Were titania present, as in the Adirondacks, then again uniform martitization must be postulated, as well as a delicate balance of leucoxenization against martitization throughout the ultramafic rocks if there are any neutral anomalous areas present, as in Newfoundland. Thus the case for near-surface oxidation-derivation of the martite does not at this juncture appear to be firmly established.

The authors have indicated (p. 784) that martitization lags leucoxenization. This would inhibit the formation of neutral areas in the aeromagnetic record. The further suggestion that martitization need not be accompanied by leucoxenization, rules out the formation of neutral areas completely, and explains the negative anomalies on the basis of the reversed remanent magnetization of the ilmenite exceeding the normal remanent magnetization of the magnetite due to the wiping out of some portion of the original and induced magnetization of the latter through alteration of a large proportion of the original magnetite to martite, through whatever cause.

Where "ilmenite may be altered to metailmenite without concomitant alteration of magnetite" (p. 784) the deduction would be that the reverse remanent magnetization would be of a low order.

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REVIEWS

The Geology of Uranium. Soviet Journal of Atomic Energy, Supplement No. 6, 1957. Translated by Consultants Bureau, Inc., New York, New York, 1958. Pp. 128. Price, $6.00.

This book contains complete translations of twelve papers dealing with certain aspects of uranium geology that were published by Soviet investigators in 1957.

Metamorphism of uranium ores, V. S. KARPENKO. Pp. 1–13; figs. 13.

Uranium deposits occurring in gently dipping strongly metamorphosed upper Paleozoic sediments are described in detail. The ore, which consists of uraninite, chalcopyrite, and minor pyrite, is found chiefly in thinly banded black silty sandstones. Mineralization of the host rock is distinctly bedded with locally enriched lenses, layers, and nodules. A diabase intrusive that cuts the host rocks is shown to be unrelated to the uranium mineralization. Although the geologic, petrographic, and mineralogical characteristics of these deposits do not conclusively invalidate a hydrothermal origin, the author concludes that metamorphism resulted in the redeposition and concentration of syngenetically deposited uranium.

The nature of sedimentary-metamorphic uranium mineralization, R. V. GETSEVA. Pp. 14–28; figs. 6.

The author describes the occurrence of uranium ore deposits in weakly metamorphosed lower Paleozoic dolomitized limestones, micaceous-argillaceous shales, and black shales. Low grade metamorphism of varying intensity was the active mechanism concentrating uranium of syngenetic origin originally dispersed throughout the sediments. The adsorption bond between syngenetic uranium oxides and organic-rich sediments was destroyed by regional metamorphism. The uranium then migrated along porous zones to favorable sites of deposition.

The origin of uranium mineralization in coal, Z. A. NEKRASOVA. Pp. 29–42; figs. 15.

Uranium mineralization of Jurassic coal strata is localized within low-rank coals adjacent to coarse grained permeable sandstones. An epigenetic-infiltration process is proposed for these deposits whereby uranium derived from the weathering of nearby granites was deposited by ground water solutions in pyritic organic-rich sediments.

New data on Nenadkevite, V. A. POLIKARPOVA. Pp. 43–55; figs. 11.

Nenadkevite is a primary uranium mineral found principally in zones of sodium metasomatism. It is composed of quadrivalent and hexavalent uranium, silica, rare earth elements, calcium, magnesium, lead, and water. Uranium may interchange with calcium and magnesium and this substitution imparts a darker color to the mineral as well as an increase in specific gravity and index of refraction. The lead is of radiogenic origin and thorium is invariably present in small amounts.

It is possible that the mineral is an end-member of the series thorite-uranothorite-nenadkevite.

The hydrous uranyl and ammonium phosphate (Uramphite), $NH_4(UO_2)(PO_4) \cdot 3H_2O$, Z. A. NEKRASOVA. Pp. 56–60; figs. 4.

Uramphite is a pale green mineral found in the oxidized zone of uranium coal deposits. It occurs as small rosettes, lichen-like aggregates, and dense patches on fractures in the coal. The author attributes its formation to solutions containing abundant ammonium ion, derived from the decay of organic matter, circulating in the zone of oxidation.

Ursilite—a new silicate of uranium, A. A. CHERNIKOV, O. V. KRUMETSKAIA, and V. D. SIDEL'NIKOVA. Pp. 61–65; figs. 2.

Ursilite is a lemon-yellow uranium silicate forming earthy or nodular incrustations along joints in quartz porphyries. It is commonly associated with kaolinite and calcite and more rarely with uranophane, sklodowskite, and kasolite. Ursilite is a member of a calcium-magnesium isomorphic series and is distinguished from other uranium silicates by its optical properties.

Conditions of formation of natroautenite, A. A. CHERNIKOV. Pp. 66–69; figs. 1.

This mineral was discovered by the author in a fault zone cutting granodiorite. Numerous hypogene minerals occur in this zone but natroautunite was the only uranium mineral found between 3 and 10 m depth. Ground water analyses suggest that natroautunite forms where sodium is more abundant than calcium as the cation in the circulating waters of this zone.

Hydrothermal synthesis of uraninite, G. P. SIDOROV and R. P. RAFAL'SKII. Pp. 70–73; figs. 6.

The authors synthesized uraninite crystals by placing a slice of shale and several milliliters of uranyl sulfate in a quartz flask, evacuating the flask, heating it for several days at 300° C, and plunging the container in cold water. Uraninite was observed to precipitate chiefly in those parts of the shale containing abundant organic matter. Some uraninite formed metasomatically within the organic-rich shales by partly replacing the quartz in the interstices between grains.

Thermal investigations of some uranium minerals. Ts. L. AMBARTSUMIAN. Pp. 74–102; figs. 24; tbls. 36.

This paper presents a systematic study of the physiochemical properties of ten minerals characterized by hexavalent uranium. In addition to thermal and dehydration analyses performed on these minerals, the author has included optical, X-ray, fluorescent, and chemical data. These minerals undergo profound transformations with increasing temperature, and dissociate with the separation of uranium oxides on melting. However, the lattices of non-volatile cation-bearing minerals are found to be more temperature-resistant.

The radiometric method of determining uranium content in ore samples, V. L. SHASHKIN and I. P. SHUMILIN. Pp. 103–110; figs. 1.

The authors present the theoretical background, apparatus, procedure, and current status of the beta-gamma radiometric method for determining uranium content in ore samples. The results of their radiometric analyses are found to be as precise as chemical analyses utilizing the phosphate method.

The ratio of beta and gamma radiation in natural radioactive elements, V. L. SHASHKIN, I. P. SHUMILIN, and M. I. PRUTKINA. Pp. 111–118; figs. 6.

When making radiometric determinations of radioactive elements, it is necessary to know the ratios of beta and gamma radiation for the different elements of the equilibrium uranium series, and equilibrium thorium and potassium. Since theoretical calculation of these ratios and calculation of the spectral sensitivity of counters are complex and yield results of unsatisfactory precision, they are best obtained through experimental determinations. The authors present their experimental data for counters of varying wall thickness and utilizing both aluminum and lead filters.

Methods and techniques of aerogeophysical prospecting for uranium deposits in foreign countries, IA. G. OGANESOV, T. I. GVAIMA, IU. V. ROSCHIN, and V. I. ZUBOVA. Pp. 119–126; figs. 1.

This paper consists chiefly of a review compiled from foreign literature of methods, techniques, and apparatus used for airborne geophysical prospecting for uranium deposits in the United States, Canada, and Australia.

Although many of the ideas presented in this collection of papers have been previously advanced by Western geologists, the new information pertaining to uranium minerals will be of particular interest to mineralogists. The individual texts are well illustrated with appropriate diagrams and the complete bibliographies include many foreign authors. The geologic descriptions are generally adequate but unfortunately all geographic information has been omitted. Geologists engaged in the field of uranium geology will find this book very informative and a useful reference.

CYRUS W. FIELD

YALE UNIVERSITY,
NEW HAVEN, CONN.,
Jan. 26, 1959

Mineralogische Tabellen. BY HUGO STRUNZ. Third edition, 1957. Pp. x + 448; figs. 70. Akad. Verlag. Geest and Portig K.-G., Leipzig. Price, DM 34 =$7.82.

This book has four parts: I, General introduction to crystal chemistry, giving (p. 1–32) a summary of important concepts and (p. 33–76) descriptions of crystal structures found among minerals; II, A systematic list (p. 77–348) of valid minerals—about 2,400 in all, with chemical formula, crystal symmetry group, and unit cell data if known. These are arranged according to the universally used crystal-chemical classification; III, Index of names (p. 349–428) including 3,800 obsolete ones with synonyms or other indications showing reasons for rejection; IV, A formula index (p. 429–448).

Part I has been enlarged and improved, and Part IV has been added, since the publication of the second edition in 1949. Moreover, the references now included in Part II are much more numerous than before. In all, more than 6,200 names are now indexed. The addition of only about a dozen more entries showing names that differ greatly in spelling or form in foreign languages would make this list so complete that even those totally unfamiliar with German could use the book nearly as effectively as others more fortunately educated. Examples in this category are few, but rather important: iron = *Eisen*; garnet = *Granat*; lead = *Blei*, and perhaps a dozen more. Most such cases are already listed including bournonite (*Bournonit, Raedelerz*) and the "*—glanz*" and "*—kies*" minerals.

Strunz's tables need no recommendation to those familiar with earlier editions; they are commended very highly to those readers not so well acquainted, including even those who are not very familiar with German.

H. WINCHELL

YALE UNIVERSITY,
NEW HAVEN, CONN.,
Feb. 11, 1959

The Stratigraphy of Western Australia. BY J. R. H. MCWHAE, P. E. PLAYFORD, A. W. LINDER, B. F. GLENISTER, AND B. E. BALME. Pp. 161; figs. 10; tbls. 9; maps 1. Melbourne University Press, New York: Cambridge University Press, 1958. Price, $8.50.

The authors have not only integrated published data, but have also incorporated much unpublished material contributed by the West Australian Petroleum Pty. Ltd., the Commonwealth Bureau of Mineral Resources, and the University of Western Australia.

Geologically, the area consists of a Precambrian land mass, on which essentially six sedimentary basins developed during Paleozoic time. Evidence of post-Proterozoic tectonics is found in all the sedimentary basins, the last main phase occurring in late Tertiary time.

The stratigraphy is considered in historical sequence. For each time unit, the distribution of sediments is discussed, and the succession in each basin or area concerned is described. Descriptions are comprehensive, and numerous references are made to the literature. However, methods of correlation are not always clear, and perhaps more attention might have been given to facies changes. Stratigraphic columns are presented, but there are no cross sections. A commendable feature is the series of paleogeographic maps. The tectonic history is summarized in the last chapter.

R. F. LAGANZA

YALE UNIVERSITY,
NEW HAVEN, CONN.,
Feb. 9, 1959

A Translation of Geochemistry. Pp. 130. Geochemical Society, Ann Arbor, Michigan, 1958. Price, $20.00 per year ($10 to educational institutions and members of Geochemical Society).

This is No. 1 of a series of translations of the Russian journal Geokhimiya, which appears eight times a year. The translation and publication is by the Geochemical Society, aided by a grant from the National Science Foundation. The translation editor is Earl Ingerson and the managing editor is Prof. E. Wm. Heinrich of the Mineralogical Laboratory of the University of Michigan who will receive subscriptions.

This first number contains translations of ten articles by Russian scientists. The articles deal with such subjects as the ionium age determination of marine sediments, free hydrogen in the earth's crust, x-ray investigations of uranium oxides, boron-magnesium skarns, evolution of rocks during metamorphism, distribution of Co, Ni, and Cu in hydrothermally altered rocks, oxidation of cobalt and nickel arsenides, rhenium in molybdates, Zr/Hf ratios in zircons, and chemistry of titanium in intrusive process of granitic rocks.

Each article is preceded by an abstract and followed by a bibliography, which is almost exclusively Russian. The book is nicely printed and covered. Each number will bring to the English-speaking world some of the current Russian research in geochemistry.

This number is a good start, and we wish the Geochemical Society all success in the undertaking.

Introduction to Geophysics. By Benjamin F. Howell, Jr. Pp. 399; Illust. McGraw-Hill Book Co., New York, 1959. Price, $9.00.

The cover jacket states, "This is the first comprehensive text in English designed to treat solid-earth geophysics at the undergraduate level." It does give a broad survey of the field, and uses relatively simple terms to do so. However considerable mathematics is involved for an elementary undergraduate text.

The chapter headings give some idea of the scope. They include the origin of the earth and moon, geochronology, temperatures, seismic waves, seismology, cause of earthquakes, mass, movement, shape and size of the earth, density and elastic constants, measurement of gravity, isostacy, tectonic forces, origin of the continents, continental drift, tectonics, mountain building, geomagnetism, terrestrial electricity, geomagnetic, and geoelectric instruments. The last chapter is the only one that touches lightly on certain phases only of geophysical prospecting.

It is a comprehensive and excellent text and reference book.

Géologie de l'Uranium. By Marcel Roubault. With the collaboration of Georges Jurain. Pp. 462; figs. 205. Masson et Cie., Paris, 1958. Price, 6,000 francs.

The author of this volume is a professor at Nancy, director of the National School of Applied Geology and Prospecting, and President of the Mining Committee of the Commission of Atomic Energy.

The book is divided into three parts—I, minerals, prospecting, and generalities; II, description of the principal deposits of the world; and Part III, conclusions. Part I gives a description of all of the uranium minerals, covering 50 pages, and then takes up the various properties of uranium minerals that can be utilized for prospecting. This is followed by description of all the methods used for uranium prospecting. The generalities consist of the distribution of uranium and thorium in the rocks and the classification and discussion of the various types of uranium deposits.

In Part II, which constitutes about two-thirds of the book, the author describes the principal deposits of the world, taking them up by continents and countries, with subdivision according to the type of deposit. The Russian satellite countries are included as is also Russia, but the information on Russian deposits is very sketchy, being based on pre-war references.

Part III is quite short and consists of a discussion of reserves of uranium and thorium, economic aspects, and problems of reserves. The book is concluded with an appendix on thorium, in which are given the minerals, prospecting, character of deposits, and description of the principal deposits of the world. An addendum of four pages gives a description of Blind River in Canada, and recent deposits in Japan.

Among the many illustrations are two beautifully colored plates containing twelve photographs of uranium minerals.

The book is intended for prospectors, engineers, geology students, chemists, industrialists, atomic commission and anyone interested in uranium. It is the most complete book that has yet been published on uranium.

BOOKS RECEIVED

JAMES M. ALLEN AND JOHN W. SALISBURY

The Rock Hunter's Field Manual—A Guide to the Identification of Rocks and Minerals. D. K. FRITZEN. Pp. 207; figs. 62. Harper & Bros., New York. 1959. Price, $3.50. *Formation and appearance of rocks; how to determine physical properties of minerals; color key, crystals; descriptions and uses, and chemical compositions.*

A Guide to Nuclear Energy, R. F. K. BELCHEM. Pp. 77; figs. 13. Philosophical Library, New York. Price, $3.50. *Theory of nuclear reaction and the way nuclear power reactors work; in simple language.*

Regional Metamorphism of the Gosaisyo-Takanuki District in the Central Abukuma Plateau. AKIHO MIYASHIRO. Pp. 53; figs. 16. Geolog. Inst., Univ. of Tokyo, 1958. *A detailed petrographic study of plutonic rocks; progressive metamorphism of basic pelletic and psammitic rocks; minerals facies.*

Mineral Assemblages and Subfacies of the Glaucophane-Schist Facies. A. MIYASHIRO and Y. SEKI. Pp. 9. Geol. Inst., Univ. of Tokyo, 1958. *Suggests two subfacies of the glaucophane-schist facies.*

Minerals Yearbook 1957. Vol. II. Fuels. STAFF OF THE BUREAU OF MINES. Pp. 480. Price, $2.25. U. S. Govt. Printing Office, Washington, 1959. *Statistics of production and use of mineral fuels.*

Minerals Yearbook 1957. Vol. III. Area Reports. STAFF OF THE BUREAU OF MINES. Pp. 1244. Price, $4.00. U. S. Govt. Printing Office, Washington, 1959. *Statistics of mineral production for each state and territory.*

Atomic Industrial Progress and Second World Conference July-December 1958. U. S. ATOMIC ENERGY COMMISSION. Pp. 386; figs. 47. Price, $1.25. U. S. Govt. Printing Office, Washington, 1959. *Summary of progress in the uses of atomic power and techniques in industry, medicine and the military. Short summaries of research projects, organization and activities of the Commission.*

Scientific Research and Development in Colleges and Universities. Expenditures and Manpower 1953–54. Pp. 173; charts 6, tbls. 62. Price, $1.00. National Science Foundation, Washington, 1958. *An evaluation of the moneys and manpower used to promote basic research and science education in American colleges and universities.*

Angular Relations of Lines and Planes With Application to Geologic Problems. D. V. HIGGS and GEORGE TUNELL. Pp. 43; pls. 10; figs. 23. Price, $2.75. W. C. Brown Co., Publishers, Dubuque, Iowa, 1959. *Basic elements of the stereographic net and spherical trigonometry as applied to geology, with ten illustrating problems.*

The Cambrian Trilobite Redlichia: Organization and Generic Concept. A. A. ÖPIK. Pp. 51; pls. 6; figs. 9. Australia Dept. National Development, Bull. 42, Canberra, 1958. *Detailed discussion of occurrence, forms and generic types of the Cambrian trilobite Redlichia found in Western Australia.*

Bulletin des Séances No. 6. Pp. 137; figs. 16; tbls. 26. Price, F.180. Académie Royal des Sciences Coloniales, Bruxelles, 1958. *Several papers dealing with: sociology, food chemistry, geochemistry of river waters and climatology. In French.*

Caribbean Geological Conference Report of the First Meeting Held at Antigua, B.W.I., December, 1955. Pp. 70; figs. 7. The "Argosy" Company, Ltd., Demerara, 1958. *Abstracts of papers presented at the conference. Subjects range through mineral resources to structure and water supply.*

Studies of Silurian (Gotlandian) Algae. J. H. JOHNSON, K. KONISHI, and R. REZAK. Pp. 173; pls. 29; fig. 1; tbls. 8; maps 9. Price, $2.00. Colorado School of Mines Quarterly, Vol. 54, No. 1., Golden, 1959. *Geographic and stratigraphic distribution of Silurian algae, classification and description of species.*

La Chronique des Mines d'Outre-Mer et de la Recherche Miniere (Mensuelle) No. 263, May, 1958. Pp. 43. Bureau d'Etudes Geologiques et Minières, Paris, France. *A review of the literature on the origin of Rhodesian-Congo copper deposits, emphasizing the syngenetic theory of origin. Abstracts of works published in various parts of Africa; production statistics for the French colonies. In French and English.*

Carte Géologique de l'Afrique Équatoriale Française au 1/2,000,000. Explanatory text by GEORGES GÉRARD. Pp. 198; pls. 4; tbls. 8. French Equatorial Africa Bureau of Mines and Geology, Paris, 1958. *Map is in four parts and separate from text.*

The Geology of 1/4° Field Sheet No. 32. W. LAYTON. Pp. 66; pls. 35; figs. 3. Price, 7s. 6d. Ghana Geological Survey Bull. 24, Accra, 1958. *Alluvial cassiterite, gold, ilmenite, columbite, and tantalite are present in the area, but values are not sufficiently high to be of economic interest.*

Geology of the Barlow Lake Area Granville Lake Mining Division. W. D. TEDLIE. Pp. 23; fig. 1. Geologic map, scale 1:31680. Province of Manitoba Dept. of Mines and Natural Resources Publ. 57–2, Winnipeg, 1958. *General geology, structure and economic geology of an area 50 miles east of Lynn Lake in Northern Manitoba.*

Spilitic Rocks and Mineral Deposits. G. C. AMSTUTZ. Pp. 11; figs. 2. Missouri School of Mines Bull. 96, Rolla, 1958. *A discussion of the possible genetic relation of apilites and various types of ore deposits.*

Archeology in Washington. B. STALLARD. Pp. 64; pl. 1; figs. 34. Price, 50 cents. Washington Division of Mines and Geology Information Circ. 30, Olympia, 1958. *Both a general survey of archeology in Washington with a bibliography of more specific literature, and an explanation and introduction to the science of archeology for those not yet acquainted with the subject.*

Preliminary Report on the Geology and Water Resources of the Bitterroot Valley, Montana. R. G. MCMURTREY, R. L. KONIZESKI, F. STERMITZ, and H. A. SWENSON. Pp. 39; pls. 2; figs. 12; tbls. 6. Montana Bureau of Mines and Geology Bull. 9, Butte, 1958. *Water of good chemical quality is available in varying quantities.*

Geology of the Newman Sound Map Area Northeastern Newfoundland. S. E. JENNESS. Pp. 53; pls. 2; tbl. 1. Newfoundland Geological Survey Rept. 12, St. John's, 1958. *Undertaken primarily to ascertain the mineral potential of the area, the study indicates no economic mineral deposits to be present. Geologic map, scale 1 inch = 1 mile.*

The Geology and Mineral Resources of Athens County, Ohio. M. T. STURGEON and ASSOCIATES. Pp. 600; pls. 11; figs. 34; maps 30; tbls. 30. Ohio Geological Survey, Columbus, 1958. *Exhaustive report on the physiography, stratigraphy and bedrock geology, and economic geology of an area in southeast Ohio.*

Bibliography of Theses on Oregon Geology. H. G. SCHLICKER. Pp. 15; fig. 1; map 1. Price, 50 cents. Oregon Dept. Geology and Mineral Industries Misc. Paper 7, Portland, 1959. *List of theses, and index map showing locations of field areas.*

Future Energy Sources for Pennsylvania. J. J. SCHANZ, JR., and OTHERS. Pp. 166; figs. 26; tbls. 18. Pennsylvania State University Mineral Experiment Station Circ. 53, University Park, 1958. *The futures of hydroelectric power, oil, gas, coal, and atomic power are evaluated.*

Geología y Mineralización del Depósito de Plomo de Matagente, Cerro de Pasco. C. C. AMSTUTZ and H. J. WARD. Pp. 13–31; pl. 1; figs. 8. Geological Society of Peru, First National Congress of Geology, Vol. 30, Lima, 1956.

The Mining Industry of the Province of Quebec in 1957. Pp. 147; figs. 2; Pls. 8; tbls. 64. Quebec Dept. of Mines, Quebec, 1959. *Detailed account of mining operations and statistical data on mine production for 1957.*

Comanchean Stratigraphy of Kent Quadrangle, Trans-Pecos Texas. J. P. BRAND and R. K. DEFORD. Pp. 371–386; figs. 2. Texas Bureau of Economic Geology, Rept. of Investigations 34, Austin, 1958. (Reprinted from A.A.P.G. Bull. 42.) *Several new groups and formations are defined and biostratigraphically correlated with the central Texas section.*

Die Diamantvoorkomste in die Omgewing van Swartruggens, Transvaal. G. P. FOURIE. Pp. 16; figs. 5; maps 3. Price, 4 sh. 9d. South Africa Department of Mines Bull. 26, Pretoria, 1958. *Description of a diamond occurrence in limberlite in the Transvaal. In Afrikaans; English summary.*

Records of the Geological Survey of Tanganyika, Vol. V, 1955. Pp. 99; plates 23; maps 2; misc. tbls. Price, Shs. 15/. Dar es Salaam, 1958. *Eleven papers on areal geology, economic geology, engineering geology, geophysics, mineralogy and petrology.*

Bechuanaland Protectorate—Lobatsi, 1958.

Records of the Geological Survey 1956. Pp. 35; maps 3; figs. 9. Price, 5 sh. *Three areal geological reports and a report on deltan salt deposits.*

Annual Report of the Geological Survey Department for the Year Ended 31st December, 1957. Pp. 31; plates 1; tbls. 2; geological map, scale 1:2,000,000. *Organization and activities of the Survey during 1957.*

Congo Belge, Leopoldville, 1958.

On the Paragenesis of Copper Ores. PAUL BARTHOLOMÉ. Pp. 31; tbls. 3. Studia Universitatis "Lovanium," Faculte des Sciences. *Correlation of the thermodynamic properties of copper and sulfur with natural occurrences. In English.*

African Charnockites and Related Rocks. R. A. HOWIE. Pp. 14; tbls. 3. Bull. 8, Fasc. 2, Service Geologique. *Detailed descriptions, including modal, chemical and spectographic analyses, of charnockitic rocks from various parts of Africa. In English.*

Divisão de Geologia e Mineralogia—Rio de Janeiro, Brasil, 1956–58.

Bol. 162. Fauna Ictiologica do Fosfato de Pernambuco. J. C. REBOUÇAS and R. D. SANTOS. Pp. 29; pls. 4; figs. 2. *The fossil material consists of teeth of*

Chrondrichthyes and Osteichthyes, and belongs to 10 species distributed in 7 genera. In Portuguese; English summary.

Bol. 164. Bibliografia e Índice da Geologia do Brasil 1945–1950. DOLORES IGLEISIAS and M. DEL MENEGHEZZI. Pp. 128. *International in scope, papers listed by author and subject.*

Bol. 165. Sôbre um Gliptodonte do Brasil. C. D. COUTO. Pp. 37; pls. 30. *The discovery of a partial skeleton of Hoplophorus euphractus Lund, 1939, in a cave deposit in Minas Gerais, accompanied by its respective caudal tube which until now was unknown, permits the description of new details regarding the genus and species. In Portuguese; English summary.*

Bol. 166. A Geologia da Serra do Mar, entre Os Picos de Maria Comprida e do Desengano. G. F. ROSIER. Pp. 58; pl. 1; figs. 34. *This part of the Serra do Mar appears to be composed of an assemblage of alpine-type nappes. In Portuguese.*

Bol. 167. Observações e Comparações Sôbre Algumas Ocorrencias Vulcânicas no Peru, no Mexico e no Brasil. O. BARBOSA. Pp. 43; figs. 60; tbl. 1. *Volcanic geology and geomorphology well-displayed in an additional 35 pages of photographs and drawings. In Portuguese.*

Bol. 168. Observções Estratigráficas e Paleontólogicas Sôbre o Calcário Corumbá. K. BEURLEN and F. W. SOMMER. Pp. 35; pls. 6. *Revision of the stratigraphical and geological studies of the Paleozoic and pre-Paleozoic formations of southern Mato Grosso, as well as correlation of these formations with others in Brazil and Bolivia. In Portuguese; summaries in English and German.*

Bol. 169. A Presença de Globidens no Cretácico Superior do Brasil. L. I. PRICE. Pp. 24; pls. 3; tbls. 2. *New occurrences of Mosasaurian remains consisting of numerous teeth provide additional information as to variety and distribution of these reptiles in South America. In Portuguese; English summary.*

Bol. 170. Contribuição ao Estudo da Bacia Costeira do Rio Grande do Norte. W. KEGEL. Pp. 52; pl. 1; figs. 7; tbl. 1. *The stratigraphy and geologic history are covered in detail to supplement previous studies.*

Bol. 171. Pesquisa de Petróleo na Bacia do Rio Corumbataí, Estado de São Paulo. Pp. 33. O. BARBOSA and F. DE A. GOMES. *Assessment of petroleum possibilities in a part of the states of Sao Paulo. In Portuguese.*

Bol. 172. Invertebrados Cretácicos do Fosfato de Pernambuco. P. E. DE OLIVEIRA. Pp. 27; pls. 2; fig. 1. *Description of marine invertebrate forms found in phosphate beds near Pernambuco. In Portuguese; English summary.*

Bol. 173. Restos Vegetais das Camadas Picos, Devoniano Inferior do Piauí. R. KRÄUSEL and E. DOLIANITI. Pp. 19; pls. 5. *Specimens of Palaeostigma sewardi, Protolepidodendron kegeli, Archaeosigillaria picosensis, and Spongiophyton are described. In Portuguese.*

Bol. 174. Carvão Mineral na Bacia Tocantins-Araguaia. O. BARBOSA and F. DE A. GOMES. Pp. 34; pls. 5. *Stratigraphy and biostratigraphy of coal-bearing formations with recommendations for development. In Portuguese.*

Bol. 175. O Projeto Araguaia. J. R. DE A. RAMOS. Pp. 30; figs. 18. *Report on a project now in progress to prepare maps and interpret aerial photographs of a large area in east central Brazil. In Portuguese.*

Bol. 176. A Faixa Costeira Meridional de Santa Catarina. J. PIMIENTA. Pp. 104; pls. 15; tbls. 4. *Study of the geomorphology and petrology of the coastal sediments. In Portuguese and French.*

Bol. 177. Bibliografia e Índice da Geologia do Brasil 1951–1955. DOLORES IGLESIAS and M. DE L. MENEGHEZZI. Pp. 80. *International in scope, papers listed by author and subjects.*

Bol. 178. *Annonaceae* Fósseis da Bacia Terciária de Fonseca, Minas Gerais. LÉLIA DUARTE. Pp. 32; pls. 3; figs. 3; tbl. 1. *A study of fossil leaves of Tertiary age. In Portuguese.*

Bol. 179. Equinóides Miocênicos da Formação Pirabas. M. E. C. MARCHESINI SANTOS. Pp. 23; pls. 5; tbls. 4. *Description of fossil echnoids found in marine limestone. In Portuguese; English summary.*

Bol. 180. Contibuição à Petrografia do Distrito Federal. R. A. BARBOSA. Pp. 40; pls. 8. *A petrographic study of basalt and diabase of northern Brazil. In Portuguese.*

Bol. 181. Dicotiledôneo Fóssil da Formação Barreiras, Estado de Sergipe. DIANA MUSSA. Pp. 24; pls. 4; figs. 3. *A study of silicified wood of Pliocene age found in Eastern Brazil. In Portuguese; English abstract.*

Bol. 182. Conífera Fóssil do Carbonífero Superior de Santa Catarina. DIANA MUSSA. Pp. 23; pls. 4; figs. 3. *Description of fossil conifer found in upper Carboniferous beds in southern Brazil. In Portuguese; English abstract.*

Bol. 184. Estudos Geológicos no Norte do Ceará. W. KEGEL, E. P. SCORZA, and F. DAS CHAGAS COELHO. Pp. 42; pls. 2; figs. 6. *Geologic reconnaissance in eastern Brazil. In Portuguese; German summary.*

Relatório Anual do Diretor 1957. Pp. 157; pls. 9; figs. 3. *Summary of work accomplished and in progress.*

Mapa Geológico do Carbonífero da Bacia Tocantins—Araguaia. O. BARBOSA and F. GOMES. *Separate geologic map showing the areal distribution of the Piauí formation.* Scale, 1 cm.: 10 km.

British Guiana Geological Survey—Georgetown, 1958.

Bull. 31. A Brief Appraisal of Ground-Water Conditions and Proposed Program for Water-Resources Investigations in the Coastal Artesian Basin of British Guiana. G. F. WORTS, JR. Pp. 52; pl. 1; tbls. 12. Price, $1.00. *Owing to the possibility of sea-water intrusion into coastal artesian wells, other supplemental sources of supply should be investigated.*

Report on the Geological Survey Department for the Year 1957. Pp. 75; pls. 3. *Summary accounts of the year's field work.*

University of California Publications in Geological Sciences—Berkeley, 1958.

Vol. 34, No. 1. Geology and Paleontology of the Pleasanton Area Alameda and Contra Costa Counties California. C. A. HALL, JR. Pp. 90; pls. 15; figs. 4; tbls. 4. *Several alterations of and additions to the stratigraphy are made. Geologic map, scale 1 inch: 3,100 feet.*

Vol. 34, No. 2. The Pliocene Verdi Flora of Western Nevada. D. I. AXELROD. Pp. 91–160; pls. 12; figs. 2; tbls. 7. *The flora indicates a Middle Pliocene average January temperature at least 10° F. higher, and a frost-free season fully two months longer, than at Verdi today.*

Canada Department of Mines and Technical Surveys—Ottawa, 1958.

Publications of the Dominion Observatory Vol. XIV. Bibliography of Seismology. Author Index 1947–1956. W. E. T. SMITH. Pp. 14. Price, 25 cents. *Index of authors who have published on the subject between 1957 and 1956.*

Publications of the Dominion Observatory Vol. XXII. Bibliography of Seismology No. 1. W. E. T. SMITH. Pp. 29. Price, 25 cents. *A bibliography of the literature of seismology January-June, 1957.*

Publications of the Dominion Observatory Vol. XXII. Bibliography of Seismology No. 2. W. E. T. SMITH. Pp. 24. Price, 25 cents. *A bibliography of seismological literature published during the period July-December, 1957.*

Map of Sudbury, Algoma, Timiskaming, Nipissing, Manitoulin, and Parry Sound Districts, Ontario. Map 1063A. *Covers geology of pertinent mining districts, but much of the territory between is blank. Scale, 1: 506,880.*

Illinois Geological Survey—Urbana, 1959.

Circ. 263. Electrokinetics. I.—Electroviscosity and the Flow of Reservoir Fluids. N. STREET. Pp. 18; figs. 6; tbl. 1. *The theory underlying electroviscous effects is simply developed and some calculations as to its order of magnitude are presented.*

Circ. 264. Determination of Acidic Groups in Coal Tars by Non-Aqueous Titration. T. P. MAHER. Pp. 8; figs. 4; tbls. 4. *Investigation of acid groups and ratio of strongly to weakly acid groups and its relation to carbonization temperature.*

Indiana Geological Survey—Bloomington, 1958.

Bull. 13. Miospore Analysis of the Pottsville Coals of Indiana. G. K. GUENNEL. Pp. 91; pls. 6; figs. 20; tbls. 11. Price, $1.50. *Discussion and illustration of the use of miospore types and abundances in the correlation of coal beds.*

Bull. 14. Cambrian and Ordovician Stratigraphy and Oil and Gas Possibilities in Indiana. A. M. GUTSTADT. Pp. 100; pl. 1; figs. 17; tbls. 8. Price, $1.50. *Stratigraphy of early Paleozoic rocks and possibilities for oil and gas exploration.*

Rept. of Progress 12. Lightweight Aggregate Potentialities of Some Indiana Shales. H. H. MURRAY and J. M. SMITH. Pp. 40; pl. 1; figs. 7; tbls. 7. Price, 75 cents. *Use of some Indiana shales for making lightweight aggregate and discussion of properties essential for this use.*

Geological Survey of Japan—Hisamoto-chō, Kawasaki-shi, 1958.

Exploratory Text of the Geological Map of Japan. Imari (Fukuoka-69). I. IMAI, K. SAWAMURA, and T. YOSHIDA. Pp. 88; figs. 35; tbls. 10. Map, scale 1: 50,000. *Areal geology of region in northern Kyushu underlain by Tertiary marine sediments and lavas. There are two coal fields in the area. In Japanese; English summary.*

Explanatory Text of the Geological Map of Japan. Tsumago (Kanazawa-85). N. YAMADA and M. MURAYAMA. Pp. 40; pls. 4; figs. 12. Map, scale 1: 50,000. *Areal geology and petrology of an igneous and metamorphic terrain in central Japan. In Japanese; English summary.*

Explanatory Text of the Geological Map of Japan. Ishikari (Sapporo-12). T. KAKIMI. Pp. 53; figs. 16; tbls. 7. Map, scale 1: 50,000. *Areal geology of an area north of the city of Hokkaido. Bedrock formations consist of Tertiary sedi-*

ments overlain by sand, gravel and clay of Pleistocene age. The Ishikari oil field, producing since 1903, is in the area. In Japanese; English summary.

Explanatory Text of the Geological Map of Japan. Mitai (Kagoshima-33). M. SAITO, N. KAMBE, and M. KATADA. Pp. 91; figs. 22. Map, scale 1:50,000. *General geology of a region in S.W. Japan underlain by Paleozoic and later sediments cut by Mesozoic and Tertiary intrusives. Bedded deposits of iron and manganese and veins containing tin, copper, lead, zinc and iron sulphides are worked in the area. In Japanese; English summary.*

Explanatory Text of the Geological Map of Japan. Katsumoto, Gonoura & Ashibe (Fukuoka-30, 39, 40). K. MATSUI. Pp. 36; figs. 15. Maps (3), scale 1:50,000. *Geology of three contiguous areas underlain by sediments and lavas of Tertiary and Quaternary age. In Japanese; English summary.*

Rept. 181. Palynological Study on Japanese Coal. II. Pollenstratigraphical Investigations in the Coal Fields, Middle Hokkaido. S. TOKUNAGA. Pp. 51; pls. 8; figs. 34; tbls. 5. *An investigation of the types and distribution of pollen species in the coal fields of Middle Hokkaido. In Japanese; English abstract.*

Bulletin—Vol. 9, No. 9. Pp. 75; figs. 61; pls. 4. *Four papers: Paleogene molluscs; ore deposits; electrical prospecting for ground water; and ground water for industrial use. In Japanese; English abstracts.*

Bulletin—Vol. 9, No. 10. Pp. 78; figs. 65. *Five papers dealing with the occurrence of wollastonite in various parts of Japan. One paper on coal field gases. In Japanese; English abstracts.*

Bulletin—Vol. 9, No. 11. Pp. 77; figs. 79. *Six papers: three dealing with ore deposits; one each on petrology, seismic prospecting, and natural gas. In Japanese; English abstracts.*

Kansas Geological Survey—Lawrence, 1958–1959.

Bull. 135. Geology and Ground-Water Resources of Kansas River Valley Between Wamego and Topeka Vicinity. H. V. BECK. Pp. 88; pls. 8; figs. 12; tbls. 7. *The Illinoian and Wisconsinan terrace deposits and Wisconsinan and Recent alluvium are the most prolific sources of ground water.*

Miscellaneous Rept. Research and Activities of State Geological Survey of Kansas. GRACE MUILENBERG. Pp. 48; figs. 35. *Organization, operation and research activities of the geological survey.*

Oil and Gas Invest. 19. Preliminary Regional Structural Contour Map on Top of the Lansing Group (Pennsylvanian) In Kansas. D. F. MERRIAM, R. L. WINCHELL, and W. R. ATKINSON.

North Dakota Geological Survey—Grand Forks, 1958–1959.

Thirtieth Bienniel Report. W. M. LAIRD. Pp. 20; pls. 3. *Summary of work accomplished and in progress.*

Rept. of Investigation 30. Madison Subcrop-Spearfish Isopach Map-Bottineau Area. S. B. ANDERSON and C. G. CARLSON. *Short discussion included on map margin. Scale, 1 in.: 2 1/2 miles.*

Rept. of Investigation 31. Mississippian Possibilities. S. B. ANDERSON. Pp. 9; figs. 8; tbls. 2. *Report on Upper Madison group facies in northwestern North Dakota may improve correlation tasks.*

Circ. 5 Revision. Pp. 178. *Seventh revision of Circular 5 containing all well-records received through January 29, 1959.*

Ontario Department of Mines—Toronto, 1959.

Sixty-sixth Annual Report. Vol. LXVI, Pt. 5, 1957. Geology of Boston Township and Part of Pacaud Township. K. D. LAWTON. Pp. 52; pls. 13; figs. 5. Map, 1 in.: 1,000 ft. *General geology, structure and economic geology of an area immediately south of the Kirkland Lake gold camp. A large low-grade iron deposit occurs in the area.*

Sixty-sixth Annual Report. Vol. LXVI, Pt. 6, 1957. Geology of Falconbridge Township. J. E. THOMSON. Pp. 36; pls. 5; figs. 12. *First detailed geological survey (1: 12,000) in the Sudbury area by the Ontario Department of Mines. Geologic map of Falconbridge Township, scale, 1: 12,000. Geologic map of the southeast part of the Sudbury Area, scale 1 in.: 1 mi.*

Sixty-sixth Annual Report. Vol. LXVI, Pt. 7, 1957. Geology of Bristol Township. S. A. FERGUSON. Pp. 42; pls. 8; figs. 7. *Detailed geologic survey (1: 12,000) directly along strike from the Porcupine gold area.*

Serviços Geológicos de Portugal—Lisboa, 1958.

Tomo XXXIX. Communiçacões dos Serviços Geológicos de Portugal. Pp. 125; pls. 42; figs. 34. *A number of papers dealing largely with archaeology. In Portuguese.*

Carte Géologique du Portugal—Notice Explicative. DÉCIO THADEU. Pp. 10; tbl. 1. *Brief discussion of the types and distribution of Portuguese formations; stratigraphic column. In French.*

U. S. Geological Survey—Washington, D. C., 1958–59.

Bull. 1028-H. Geology of Little Sitkin Island Alaska. G. L. SNYDER. Pp. 169–210; pls. 4; figs. 5; tbls. 4. *Perhaps 77,000 tons of recoverable sulfur of volcanic origin are present on the island, but economic development in the near future seems improbable.*

Bull. 1042-Q. Pegmatites of the Middletown Area Connecticut. F. STUGARD, JR. Pp. 613–683; pls. 2; figs. 2; tbls. 16. *Feldspar reserves are adequate to continue mining on the present scale for many years, but no beryl deposits capable of sustaining an operation for beryl alone have been discovered. Geologic map, scale 1: 12,000.*

Bull. 1046-M. Reconnaissance Investigation of Uranium Occurrences in the Saratoga Area Carbon County, Wyoming. J. G. STEPHENS and M. J. BERGIN. Pp. 321–338; pls. 3; figs. 5; tbls. 4. Price, 55 cents. *Uranium occurs largely as coatings on pediment sediment and is believed to have been formed by solution and redeposition of uranium by groundwater.*

Bull. 1046-N. Preliminary Study of Radioactive Limonite in Colorado, Utah, and Wyoming. T. G. LOVERING and E. P. BERONI. Pp. 339–384; pl. 1; figs. 14; tbls. 14. Price, 35 cents. *Nine radioactive-limonite localities of different types were sampled in an effort to establish criteria for differentiating limonite outcrops associated with uranium or thorium deposits from limonite outcrops not associated with such deposits.*

Bull. 1052-E. Physical Behavior and Geologic Control of Radon in Mountain Streams. A. S. ROGERS. Pp. 187–211; pls. 3; figs. 10. Price, 40 cents. *Higher radon concentrations generally can be related to specific stratigraphic horizons in the several drainage areas studied. Thus, lithologic units that act as the primary aquifers can be identified. In one area, thrust faults were found to control the influx of ground water into the stream.*

Bull. 1052-F. Scintillation Counters for Geologic Use. W. W. VAUGHN, V. C. RHODEN, E. E. WILSON, and HENRY FAUL. Pp. 27; pls. 3; figs. 12. Price, 35 cents. *Discussion of three types of scintillation counters, a hand held model, a car or aircraft model, and a well-logging instrument.*

Bull. 1052-G. A Comparison Among Caliper-Log, Gama-Ray-Log, and Other Diamond-Drill-Hole Data. C. M. BUNKER and H. C. HAMONTRE. Pp. 7; pls. 2; figs. 3. Price, 15 cents. *Correlation of drill hole diameter with gamma ray log. No significant effects in normal drilling.*

Bull. 1058-B. Geology and Ore Deposits in the Reid Inlet Area, Glacier Bay, Alaska. D. L. ROSSMAN. Pp. 33–59; pls. 2; figs. 5. *The area contains many gold-bearing quartz veins. The chief factor which has inhibited continued prospecting and mining in the area seems to be the small size and discontinuous character of the veins.*

Bull. 1058-D. Geology and Coal Resources of the Little Susitna District Matanuska Coal Field Alaska. F. F. BARNES and DANIEL SOKOL. Pp. 17; pls. 5; figs. 3. *Report on occurrences of subbituminous coal in south central Alaska, not considered to be economically exploitable.*

Bull. 1074-B. Reconnaissance for Radioactive Minerals in Washington, Idaho, and Western Montana 1952–1955. P. L. WEIS, F. C. ARMSTRONG and SAMUEL ROSENBLUM. Pp. 47; pl. 1; figs. 2. Price, 35 cents. *Areas of most promise are in or near granitic or quartz monzonitic intrusions of probable Cretaceous age.*

Bull. 1084-A. Natural Radioactive Disequilibrium of the Uranium Series. J. N. ROSHOLT, JR. Pp. 29; figs. 4; tbls. 2. Price, 15 cents. *Discussion of the effects of the geochemical processes occurring in ore deposits on radioactive equilibrium.*

Bull. 1088. Problems in the Disposal of Acid Aluminum Nitrate High-Level Radioactive Waste Solutions by Injection Into Deep-Lying Permeable Formations. EDWIN ROEDDER. Pp. 62; figs. 6; tbls. 5. Price, 40 cents. *The difficulties and disadvantages of such a disposal method are described as well as the circumstances favoring such a method of disposal.*

Water-Supply Paper 1426. Ground-Water Resources of the Hueco Bolson Northeast of El Paso Texas. D. B. KNOWLES and R. A. KENNEDY. Pp. 185; pls. 11; figs. 14; tbls. 6. *Distribution, character and reserves of ground water.*

Water-Supply Paper 1460-E. Geological and Geophysical Study of the Preglacial Teays Valley in West-Central Ohio. S. E. NORRIS and H. C. SPICER. Pp. 199–232; pls. 2; fig. 1. Price, 55 cents. *The authors suggest a plan for prospecting the Teays Valley by geophysical methods and test drilling throughout the remainder of its course in Ohio to ascertain where it may contain outwash sands and gravels of possible importance as sources of ground-water supplies.*

Water-Supply Paper 1477. Annotated Bibliography on Artificial Recharge of Ground Water Through 1954. D. K. TODD. Pp. 115. Price, 50 cents. *International in scope, papers listed by author and subject.*

Economic Geology
Vol. 54, 1959, pp. 530–531

SOCIETY OF ECONOMIC GEOLOGISTS

The next meeting of the Society of Economic Geologists will be held in conjunction with the Geological Society of America and associated societies at Pittsburgh, Pa., November 1–4, 1959. Headquarters for the meeting will be the William Penn Hotel.

Abstracts of papers intended for presentation at the technical sessions of this meeting must be received by the Secretary prior to *July 15*. The abstracts should be informative, but they must not exceed the 250 word limit. Authors submit their abstracts in quadruplicate and should indicate the minimum time needed to present the paper. In the event employer permission to publish is required, the author should certify on the abstract form that the abstract has been cleared for publication.

In addition to the regular technical sessions, which will be based on volunteer papers as per the preceeding paragraph, the program of the Society will include a symposium on "The role of stable isotope research in the field of ore deposits." The symposium, which will consist of the reading and discussion of a group of papers prepared by invitation, is designed to review results that are being attained in this relatively new field of research, and to consider their potential value in understanding and locating ore deposits. According to present plans, the symposium will be held on *Sunday afternoon November 1*.

The Annual Meeting of the Society will be held this year in conjunction with the American Institute of Mining, Metallurgical, and Petroleum Engineers at New York, N. Y., February 15–18, 1960. Headquarters will be at the Statler Hotel. Abstracts of papers to be presented at the New York meeting must reach the Secretary of the Society on or before *August 15, 1959*. These abstracts should conform with the standards for abstracts set forth above.

Forms on which to submit abstracts can be obtained from Harold M. Bannerman, Secretary, Society of Economic Geologists, c/o U. S. Geological Survey, Washington 25, D. C.; or from Robert M. Grogan, Chairman, SEG Program Committee, 6015 Du Pont Building, Wilmington 98, Delaware.

The Penrose Medal of the Society of Economic Geologists, established in 1923 and last awarded in 1956, will again be awarded in 1959. Members of the Society are invited to nominate candidates for the 1959 Penrose Medal Award in accordance with the following percepts and procedures:

A. The Penrose Medal is awarded for "unusual original work in the Earth Sciences." While no formal rules exist concerning eligibility, it is considered that a candidate should be a person of outstanding accomplishment in the profession of economic geology (though not necessarily a member of the Society) who is able and willing to present himself in person to receive the award at the time of nomination. The death of a candidate subsequent to June 15, 1959, however, does not render him ineligible and, if selected for the award, the presentation may be made posthumously. In considering their nominations, members may wish to refer to Article III of the constitution of the Society, as published in the Proceedings, 1954–1957, which clearly defines the object of the Society.

B. Nominations by members of the Society are to be submitted in quintuplicate to Clayton G. Ball, *Chairman of the Penrose Award Committee*, who will promptly

acknowledge receipt of each nomination and distribute four copies to the members of the Committee (listed below). It is requested that nominations be prepared according to the following outline:

(1). Name, office or title, and affiliation of nominee.
(2). His date and place of birth, education, degrees, honors and awards.
(3). Major events in his professional career, including bibliography.
(4). Outstanding achievements and accomplishments which warrant his nomination.

C. Nominations may be submitted at any time up to a final deadline of June 15, 1959, after which the list of nominations will be closed. The recipient of the Award will be announced at a suitable time thereafter by the Council. The membership of the 1959 Penrose Award Committee is as follows:

KESLER, THOMAS L.
LEIGHTON, MORRIS M.
PEOPLES, JOE WEBB
VANDERWILT, JOHN W.
BALL, CLAYTON G., *Chairman* (address: Paul Weir Company, 20 North Wacker Drive, Chicago 6, Illinois)

Economic Geology
Vol. 54, 1959, pp. 532–533

SCIENTIFIC NOTES AND NEWS

CHRISTOPHER RILEY, consulting geologist, has been elected President of the British Columbia and Yukon Chamber of Mines for 1959.

DANIEL A. BUSCH, consulting petroleum geologist of Tulsa, Okla., is the 1959 winner of the George C. Matson Award of the American Association of Petroleum Geologists for the excellent presentation of his paper entitled "Prospecting for Stratigraphic Traps" at the 44th annual meeting of the A.A.P.G., held in Dallas, Tex., March 16–19, 1959.

FRANK R. HUNTER has been appointed chief geologist in the mining and exploration department of International Minerals and Chemicals Corp. at Carlsbad, N. M.

H. R. GAULT has been appointed head of the Department of Geology of Lehigh University to succeed Dr. Bradford Willard who is retiring.

WILLIS M. JOHNS was recently appointed resident geologist for the Great Northern Railway at Kalispell, Montana.

Uranium ore receipts at plants and depots in the United States during the last six months of 1958 were 2,807,008 tons. Ore fed to process was 3,011,000 tons averaging 0.255% U_3O_8. Ore reserves were 82,500,000 tons on Jan. 1, 1959.

PHILIP E. LAMOREAUX, former division hydrologist, mid-continent area, of the water resources division of the Geological Survey, has been named chief of the Survey's ground water branch. He succeeds Dr. A. Nelson Sayre who has recently been assigned to research requiring exceptionally broad experience in ground-water hydrology.

A symposium on geochemistry organized by the Commission on Geochemistry of the International Union of Pure and Applied Chemistry will be held in Göttingen, Germany, August 21–22, 1959, to be followed by two days' field excursions. The topics for discussion at the Symposium are: 1) Stable nuclides in Geochemistry; 2) Long lived radionuclides in natural systems; 3) Geochemistry of the halogens; 4) Geochemical aspects of life on earth. Introductory lectures will be held as follows: for 1) Rankama, 2) Harrison Brown, 3) Correns, 4) Oparin and Urey, who will extend invitations for further contributions.

The excursions will be a day to the Harz and another to the Zechstein salt deposits. The local chairman of the Symposium is Prof. C. W. CORRENS, Sediment-petrographisches Institut, Göttingen, Lotzestrasse 13.

ROBERT M. DREYER has resigned from Kaiser Aluminum and Chemical Corp. and has joined the geological staff of Reynolds Metals Co., Richmond, Va.

JAMES A. NOBLE has resigned his position of Professor of Economic Geology at the California Institute of Technology. He will continue to live in Pasadena and carry on consulting work for a number of companies having interests in California, British Columbia, and Alaska.

The Walker Mineralogical Club of the University of Toronto has awarded its Peacock Memorial Prize (1958) of two hundred dollars "for the best scientific paper on pure or applied mineralogy, including crystallography, mineralogy, petrology, ore genesis, and geochemistry," to Mr. R. L. MOXHAM, Burlington, Ontario, a graduate student in the Department of Geology, Hamilton College, McMaster University, for his paper on "Minor Element Distribution in Some Pyroxenes of Metamorphic Origin."

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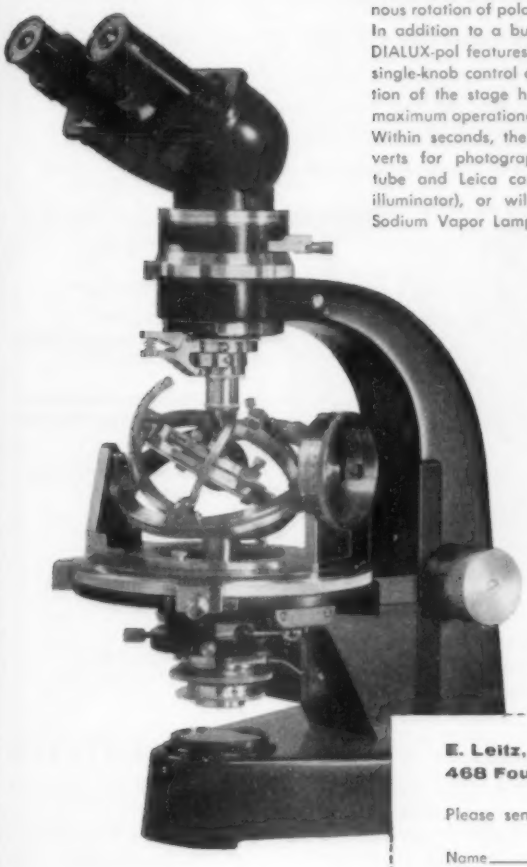

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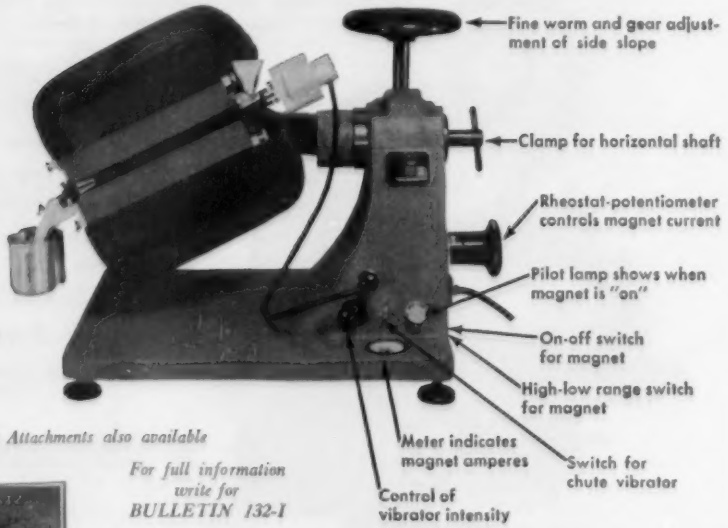
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